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SHORT-TERM SELF-MOVING TACTICAL NETWORKS IN AUSTERE ENVIRONMENTS

by

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U.S. Special Operations forces require secure and reliable network communications for Command and Control (C2) when operating in austere environments, such as enemy combatant or disaster relief operations. During these operations, current communication procedures present a significant risk to network operators who must be physically present to construct tactical networks.

An extensive amount of research has been conducted utilizing unmanned ground, air, and surface vehicles to extend communication links; however, unmanned systems generally require direct human interaction at a close range for network configuration and control. This research examines methods to increase the standoff distance for network operators working in hazardous environments by employing unmanned systems and communications equipment in the construction and deployment of a self-moving network infrastructure. Through several phases of experimentation, we demonstrate that selected unmanned ground vehicles and communications equipment can be successfully integrated to construct and mobilize tactical networks for special operations teams.

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SHORT-TERM SELF-MOVING TACTICAL NETWORKS IN AUSTERE ENVIRONMENTS

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U.S. Special Operations forces require secure and reliable network communications for Command and Control (C2) when operating in austere environments, such as enemy combatant or disaster relief operations. During these operations, current communication procedures present a significant risk to network operators who must be physically present to construct tactical networks.

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LIST OF ACRONYMS AND ABBREVIATIONS

API	Application Programming Interface
AT	Alignment and Tracking
A/D	Analog to Digital
BATS	Broadband Antenna Tracking System
BGU	Ben Gurion University
C2	Command and Control
CACTF	Combined Arms Collective Training Facility
CAN	Controller Area Network
CBL	Configurable Logic Block
CENETIX	Center for Network Innovation and Experimentation
COTS	Commercial-Off-The-Shelf
CSMA/CA	Carrier-Sense Multiple Access/ Collision Avoidance
DARPA	Defense Advanced Research Projects Agency
DB	Decibel (Dipole)
DBI	Decibel (Isotropic)
DF	Direction Finding
DoD	Department of Defense
DSSS	Direct-Sequence Spread Spectrum
EMCON	Emissions Control
ES	Electromagnetic Spectrum
ESA	Electronically Steered Antenna
FDMA	Frequency-Division Multiple Access
FPGA	Field-Programmable Gate Array
GPS	Global Positioning System
GUI	Graphical User Interface
HA/DR	Humanitarian Assistance/Disaster Relief
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
IRIS	Individual Robotic Intelligent System
IVO	Intelligent Vehicle Operator
JIFX	Joint Interagency Field Experiment
JTNC	Joint Tactical Networking Center

JTRS	Joint Tactical Radio System
LAN	Local Area Network
LASR	Laboratory for Autonomous Research
LOS	Line of Sight
MANET	Mobile Ad Hoc Network
MIMO	Multiple In Multiple Out
MIO	Maritime Interdiction Operations
MPU	Man Portable Unit
MTX	Multi-threat Experiment
NASA	National Aeronautical and Space Administration
NRL	Navy Research Lab
NOC	Network Operations Center
OFDM	Orthogonal Frequency Division Multiplexing
PLI	Position Location Information
RF	Radio Frequency
RHIB	Rigid Hull Inflatable Boat
RMP	Robotics Mobility Platform
ROIP	Radio Over IP
SA	Situational Awareness
SCI	San Clemente Island
SDK	Software Development Kit
SDR	Software-Defined Radio
SME	Subject Matter Expert
SOCOM	Special Operations Command
SPECWAR	Special Warfare
TDMA	Time-Division Multiple Access
TOC	Tactical Operations Center
TS	Top Security
UAV	Unmanned Aerial Vehicles
UDAAN	Utilizing Directional Antenna for Ad Hoc Networking
UGV	Unmanned Ground Vehicles
UMV	Unmanned Maritime Vehicles
USV	Unmanned Surface Vehicles
UUV	Unmanned Underwater Vehicles
UxV	Unmanned Vehicles

W	Watts
WMN	Wireless Mesh Network
WP	Way Point

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I. INTRODUCTION

Department of Defense Special Operations Command (SOCOM) operators require secure and reliable communications when entering contested environments. Austere environments introduce significant challenges in establishing communications links for situational awareness (SA) and command and control (C2). The key consideration in these environments is the danger they present to network operators due to possible contamination, hostile fire, or other threat conditions. To address this challenge, we propose a system of unmanned vehicles and communications equipment that can replace humans in network deployment duties, while allowing network operators to direct, observe, and maintain the network remotely.

An extensive amount of research has been conducted with unmanned vehicles participating in tactical communication link extension but it has always required onsite human interaction for configuration and control (Bordetsky & Netzer, 2010). Taking network operators out of close-proximity and allowing them to manage networks remotely to reduce the risk to human life and resources.

This research addresses methods to increase the standoff distance for network operators while working in hazardous environments by employing unmanned systems and communications equipment in the construction and deployment of a self-moving network infrastructure. We examine which specific communications equipment and unmanned vehicles can be integrated to address this problem. We execute several experiments, work with industry and Department of Defense (DoD) experts on the latest innovations, and provide our analysis for unmanned C2 network configuration.

A. SCENARIO

The president and staff have been briefed on a credible threat of stolen nuclear material being transported by a smuggling group to a remote island nation in contested waters that the U.S. is not an ally of, for imminent sale to a known terrorist organization that has recently threatened actions against Guam. During this time, political tensions and the threat of hostilities are high. The sale is set to occur within the next 12 hours but an exact timeframe is unknown. The Secretary of Defense informs the president that several ships and two Special Warfare (SPECWAR) teams are in the vicinity and can be deployed to the location within an hour to search the island. It is 30 minutes from sunset. The nuclear material is considered a threat to national security and the President approves deploying a SPECWAR team immediately.

Given two hours' notice and armed with fresh satellite imagery taken near dusk and quick intelligence preparation, the small special operations team travels aboard a U.S. Navy vessel to the remote island to search and secure the suspected nuclear material. The vessel approaches the opposite side of the island under Emissions Control (EMCON), away from the suspected smuggler encampment area, to deliver the team while reducing detection by hostile forces or the indigenous population.

The team departs the U.S. naval vessel approximately three nautical miles offshore in their Rigid Hull Inflatable Boat (RHIB) and travels at high speed towards the island to land in a small alcove that has natural cover. Approximately 1,000 yards offshore and under the cover of darkness, they cut the engine and swim with the boat the rest of the way in to avoid any noise detection. Because the mission is short-notice and their current satellite imagery was taken near dusk, they have incomplete intelligence, to include how many smugglers are there, what equipment they have, and whether the terrorist organization is also on the island. Additionally, there is a local population living on the island and it is not known whether they are sympathetic towards or supporting the government, or if they are smugglers or a terrorist group. The first order of business is to establish C2 on the island so the team can ensure SA. The team sets up a portable satellite link for voice communications back to the commander. Team members deploy on foot with backpack radios to establish communications links. The terrain is rugged with many trees. The highest visible terrain near the landing site is identified and a teammate proceeds in that direction to establish a relay in order to overcome any Line Of Sight (LOS) communication issues. As he approaches higher terrain, he is fired upon by unseen entities in dark, tropical brush. He evades the live fire but is no longer able to proceed in the direction of higher ground and back-traces his previous path to an offset location. Without a communications node elevated to a position that allows unobstructed LOS communications, the team cannot establish C2 effectively. They must complete their search in a small grid pattern, with all members in LOS, to ensure they have good communications and are able to handle any unforeseen situations. This type of search takes additional time, could jeopardize the mission, and will put the team at further risk without the necessary longer range C2 network.

The challenge with this scenario, and a variety of scenarios in which austere environments are involved, is that lives must be put at risk to establish essential communication for C2 and mission completion. Today, technological advances in unmanned vehicles allow them to be interchanged for human operator roles and perform the same work. Removing humans from network deployment and construction tasks will decrease the threat to life. Humans are one of the most expensive and valuable resources in the U.S. military and protecting life is always a top priority, regardless of mission objective.

B. RESEARCH OBJECTIVE

The purpose of this research is to identify the architectural requirements for the configuration, deployment, and operation of tactical communications networks using unmanned assets to support special operations in austere environments. The most vital assets to the DoD are human lives and as such, this research seeks to reduce the need for network operators to be physically present during communications equipment network node placement and management. We study current unmanned systems technologies that could deploy enable network operators to remotely network nodes, position them in designated locations, and adjust their position as needed. We examine different types of communication links and protocols to determine which will provide reliable and secure communications. We also test long-range communications to determine which technology solutions could best extend network control link ranges.

The research questions addressed by this thesis are:

1. What unmanned platform characteristics are suited for constructing and delivering tactical network in an austere environment?

2. What communications equipment characteristics support a short-term, self-moving tactical network in an austere environment?

The goal of this thesis is to identify the equipment and requirements for a tactical network infrastructure that could deploy and operate using remote control links. This network would reduce the need for the network operator to remain in close proximity to communications nodes and instead utilize unmanned vehicles to configure and maintain the network remotely from a Network Operation Center (NOC) or Tactical Operations Center (TOC).

C. SCOPE AND LIMITATIONS

This thesis addresses tactical communications required for special operations teams in austere environments. Our concentration is on the special warfare team's ability to maintain C2 using tactical network nodes aboard unmanned vehicles. We do not research the equipment logistics and delivery aspect of the operation nor do we analyze the reach-back communications to a ship or TOC, nor do we research internal programming parameters of unmanned system operator control units.

This research is limited by resource and time factors. We did not have access to large variety of unmanned systems; therefore, portions of the research are conceptual because various applicable sensor and communication hardware configurations could not be physically tested.

D. ORGANIZATION

This thesis comprises five chapters that detail the research process. The following is an overview of each chapter:

Chapter II provides a literature review of selected modern communications technologies. We describe antenna systems and radio communications used in tactical scenarios as well as selected unmanned vehicles currently used by the DoD and their history. We also explore previous research related to the problem and outline challenges for tactical communication architectures.

Chapter III presents a phased approach to our experimentation, which were conducted in four phases. We first participated in a multi-thread experiment that helped to identify gaps in current tactical network technology and to formulate a plan to analyze those gaps. We then compared selected unmanned systems and selected those that fit the requirements for our network. We also selected communication equipment. Finally, we conducted bench testing and field testing with the selected equipment to observe and analyze if its performance would be a feasible solution for our scenario's proof of concept.

Chapter IV provides an analysis of experiment results, observations, and recommendations.

In Chapter V, we review our findings and draw our conclusions on the research. Additionally, we present our recommendations and opportunities for future research.

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II. LITERATURE REVIEW

Our literature review focuses on understanding the history and relevant theory of radios, antennas, and unmanned vehicles with respect to how they could be utilized to construct a tactical network in a rapid, secure manner for special operations teams. We also review previous research that is pertinent to our thesis topic.

A. MOBILE AD HOC NETWORKS

Mobile Ad Hoc Network (MANET) is a system of wireless communications nodes that does not require any fixed infrastructure or existing network configuration (Bhushan, Saroliya, & Singh, 2013). It is a self-configuring and self-healing network that is easy to set up and is more flexible compared to a network that requires a preexisting infrastructure to function properly. Each network node can perform both as a host and as a relay and independently decides the best route based on the availability of the neighbor nodes (Wang, Crilly, Zhao, Autry, & Swank, 2007). If one node becomes unavailable, the dynamic topology of the network quickly adapts, and the data flow remains unaffected.

Some of the constraints of MANET architecture are power and bandwidth restrictions associated with the equipment used. MANET radios are powered by batteries and their operational time is limited (Wang, Xie, & Agrawal, 2009). Additionally, the bandwidth allocated for a MANET is shared between all nodes, and mobile radio transmitter and receiver antennas are not as powerful as those of a fixed infrastructure. However, the adaptive property, the ability to set up a network infrastructure-less and in conjunction with a fixed network system, makes a MANET a versatile network architecture choice in a tactical environment.

B. ANTENNAS

Antenna design is an essential element in any network system architecture requiring multiple nodes to communicate. Key elements such as number of nodes, distance between them, and the type of data being transmitted from one node to the other are the driving factors in choosing the correct number and type of antennas for the system. Directional and omnidirectional antenna systems have been extensively studied in wireless mess network applications. Each of these systems provides unique capabilities and challenges.

When considering the best type of antenna for a particular network construction, there are antenna properties to consider: direction or pattern, gain, and polarization (CISCO, 2007b). This thesis addresses antenna pattern and antenna gain. A radiation pattern or shape of an antenna is a graphical representation of a signal propagation as a function of space (Hill, 2001). A coordinate system is used to describe an antenna pattern as a three-dimensional formation. The horizontal x-y plane refers to the horizontal azimuth plane and x-z and y-z planes are vertical elevation planes (CISCO, 2007b).

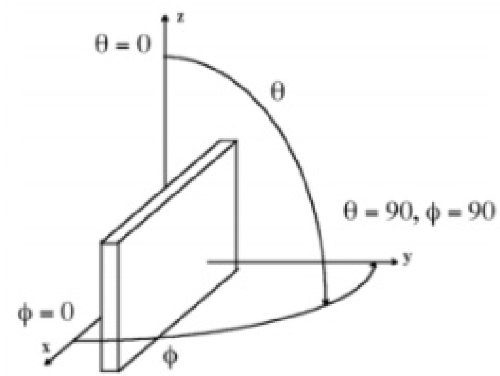


Figure 1. Antenna pattern measurement coordinate system. Source: CISCO (2007a).

An antenna gain quantifies the amount of power amplification by the antenna to a radio frequency (RF) signal (CISCO, 2007b). An isotropic radiator that has equal radiation energy in all directions is used as a one of the references for measuring antenna gain (Hill, 2001). Its gain is G=1 or 0 decibels (dBi). Another reference is a theoretical dipole with gain of 0 dB that is used when describing a gain of a dipole antenna. Using either of these two references, if an antenna has a gain of 5 dBi, that means that its radiation intensity is five times higher than radiation of an isotropic radiator using the same power. Because an antenna itself does not generate power but only directs it, the gain of the antenna only denotes the radiation intensity in a specific direction. An antenna gain of 10 dB implies the gain in the direction of maximum energy radiation (CISCO, 2007b). The radiation output power of an antenna is measured in Watts (W). It is important to note the relationship between the antenna gain, output power, and the distance a signal would travel. With every gain of 3 dB, the power would double, and for every increase in gain by 6 dB, the signal range will double (Cunningham, 2012).

1. Omnidirectional Antenna

When setting up a network with multiple nodes, communication requirements determine the type of antenna used for the network. Most radios, cell phones, and similar equipment use omnidirectional antennas. Dipole antennas are the most common omnidirectional antennas.

Figure 2. Dipole antenna. Source: Capano (2014).

The radiation energy of a dipole antenna is such that it radiates equally in all directions, which is beneficial when building a network consisting of three or more nodes. Figure 3 shows a pattern of a typical dipole omnidirectional antenna. The energy is radiated outward on the azimuth with null area along z-axis and resulting in a 3D pattern as depicted in Figure 3(b) model (CISCO, 2017a). The red and green colors in the model indicate signal strength with red being a stronger and green being a weaker signal. The azimuth plane (c) shows that the energy pattern is uniformed around 360 degrees.

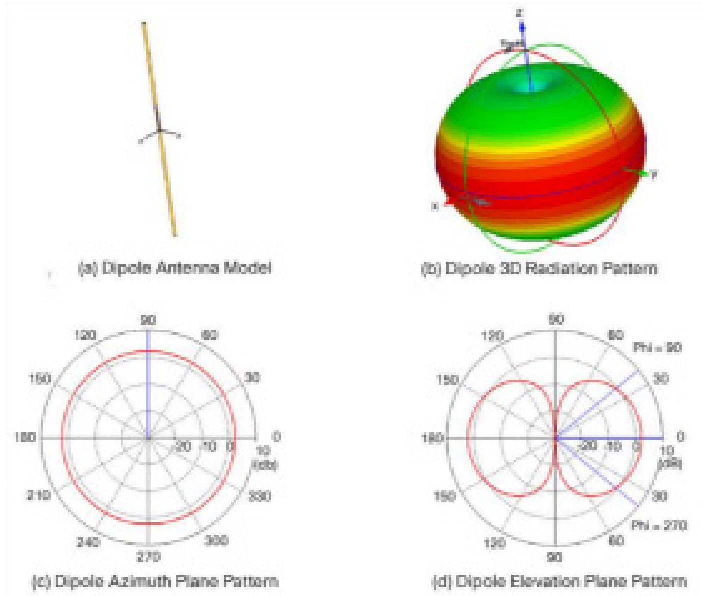


Figure 3. Omnidirectional antenna patterns. Source: CISCO (2007a).

Omnidirectional antennas are intended to be positioned perpendicular to the ground or floor to allow the maximum transmission coverage outward. The elevation of antenna should be determined by the type of environment around the antenna. Obstructions such as trees, buildings, and other communication systems can distort or even block signal transmission.

2. Directional Antenna

The use of directional antennas offers great advantages over omnidirectional antennas where point-to-point communication is required (Ramanathan, Redi, Santivanez, Wiggins, & Polit, 2005). The most common types of directional antennas are patch antenna, sector antenna, Yagi, parabolic or dish antenna, and grid antenna. The pattern of a directional antenna is concentrated in the desired direction. The graphical representation of this pattern is shown as a beam and each portion of that beam is called lobe (CISCO, 2007b).

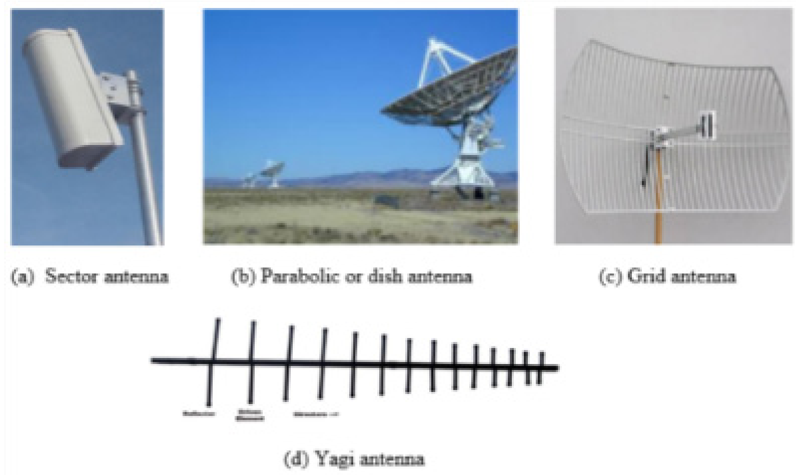


Figure 4. Directional antenna types. Source: Capano (2014).

The patch antenna pattern (Figure 5d) has one main lobe, one back lobe, and two side lobes. The main lobe extends farther than the rest to indicate the highest radiation power in that particular direction. When determining the efficiency of an antenna, the width of its main lobe, or beamwidth, is considered. Wider beamwidth indicates lower antenna gain and a narrow beamwidth yields a higher gain as the radiation is more concentrated. This property often makes this antenna a system of choice for point-to-point communications.

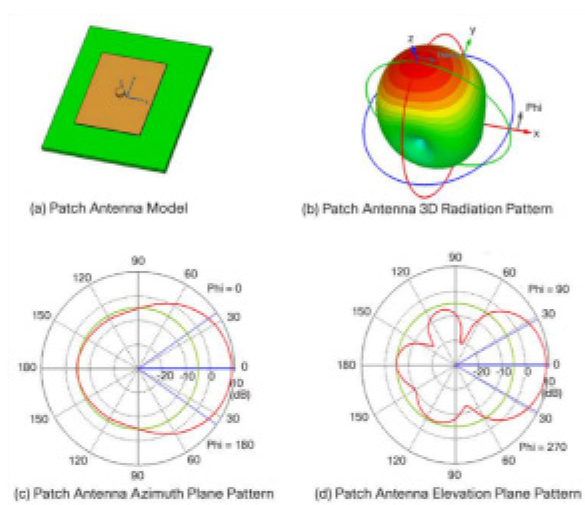


Figure 5. Directional antenna pattern. Source: CISCO (2007a).

The 360-degree coverage make omnidirectional antennas easy to set up since the network operator does not have to be concerned with the location of network nodes in relation to the antenna. A TOC might be equipped with an omnidirectional antenna allowing for communication with nodes located in different directions. The tradeoff of using an omnidirectional antenna is decreased range of transmission and reception. To transmit data over very long distances, the signal has to be concentrated in a particular direction. As the antenna beamwidth decreases, the need for additional antennas increases for a more complex network.

3. Direction Finding Antenna

When network nodes are expected to continuously adjust their positions to either improve communication links or avoid hazards, a network architecture must include self-aligning directional antennas that have an ability to adjust their bearing to maintain the link. Rohde & Schwarz (2011) argue that direction finding is becoming an essential part in any mobile communication system. With a traditional directional antenna set up, a network operator must always know the exact position and relative bearing of all network nodes, monitor their movement changes, and manually adjust the antenna orientation accordingly for continuous transmission. This task becomes increasingly difficult if the network architecture includes multiple mobile nodes and multiple directional antennas.

Some self-aligning antennas such as Broadband Antenna Tracking System (BATS) Wireless products utilize RF, GPS, or a combination of both signals for tracking and alignment between two units (Broadband Antenna Tracking System [BATS], Wireless 2017a). Some additional features may include special programming that allows the antenna to adhere to preset parameters such as distance or GPS coordinates when tracking nodes. Additionally, if a link is lost, the antenna does not require manual interference and immediately attempts to reacquire it or search for another available node (BATS Wireless, 2017a). This property is one of the major components in any self-healing tactical network.

In 2017, US Special Operations Command (SOCOM) conducted a two-day experiment, SOCOM TE 17.3, where BATS Electronically Steered Antenna (ESA) was tested (BATS Wireless, 2017b). ESA is a sectored omnidirectional antenna that uses BATS

Alignment and Tracking SW (ATS) algorithm that provides the ability to work in any frequency required. Each directional sector of the antenna enables an integration with a multiple in multiple out (MIMO) technology that is an important component of any complex MANET system.

Figure 6. ESA installed on the roof of a van. Source: BATS Wireless (2017b).

In the experiment, one ESA was installed on an 11-foot rigid-hulled inflatable boat (RHIB) and one ESA was installed on shore on a roof of a van (Figure 6). During the first test, the van remained stationary, while the RHIB was moving laterally stretching the range between the two antennas to over 3.5 miles, and during the second test, the boat was continuously moving reaching the speed of approximately 40 knots (BATS Wireless, 2017b). The data collected from this event showed that the link between the two antennas remained solid during both tests and VoIP and live HD video feed remained steady. Moreover, it was discovered, that the antenna sectors worked individually based on the relative positions of each other which prevented RF bleeding and interference (BATS Wireless, 2017b).

Some current implementations of self-aligning antennas include Direct TV cable services for cross-country semi-trailer trucks and recreational vehicles. These systems possess a great potential for military applications especially in networks that include both stationary and moving nodes.

C. RADIOS

Modern tactical communications have a four-decade old history dating back to the Vietnam War era. In the 1960s, military radios used VHF, HF, and UHF bands for infantry, over-the-horizon, and air-to air and air-to ground communications respectively (Elmasry, 2013). Non-IP radio development streamlined during the Cold War and the new generation of tactical communications radios called Link-16 emerged. Link-16 is a frequency-hopping radio with anti-jamming, long-range communications, and low signal-to-noise transmission detection capabilities (Elmasry, 2013). Its original time-division multiple access (TDMA) deployment allowed multiple users to use the same frequency channel while being assigned their own time slot to use that channel (Nelson & Kleinrock, 1985). The addition of frequency-division multiple access (FDMA) allowing multiple users to have continuous access to an assigned frequency and direct-sequence spread-spectrum (DSSS) that enabled low probability of jamming made these radios to be the most resilient and reliable wireless communications technology of its generation (Elmasry, 2013). Ultimately, Link-16 system evolved into a more sophisticated system that was integrated with many different platforms providing voice and data communications and supporting multiple missions across the DoD. However, with rapid technological advances, the need for more robust radios with enhanced capabilities exponentially increased.

1. Software-Defined Radios

In the 1980s, the DoD funded a development of tactical communications systems that could be easily upgraded and reconfigured based on mission requirements and during joint exercises or operations. Such radios became known as Software-Defined Radios (SDR), a term coined by Joseph Mitola in 1991 (Jacobsmeyer, 2012). Having to only reconfigure software for specific missions using a single hardware platform allowed for greater flexibility, reduced cost, and improved services for the military (Mitola, 1993). Mitola (1993) claimed that a software radio could be incorporated into any RF-based communication system within the same Analog to Digital (A/D) bandwidth by immediately reconfiguring itself to support the given system's signal format (Mitola, 1993). Such radio systems are used today in a variety of military and civilian applications supporting data, voice, and imagery products.

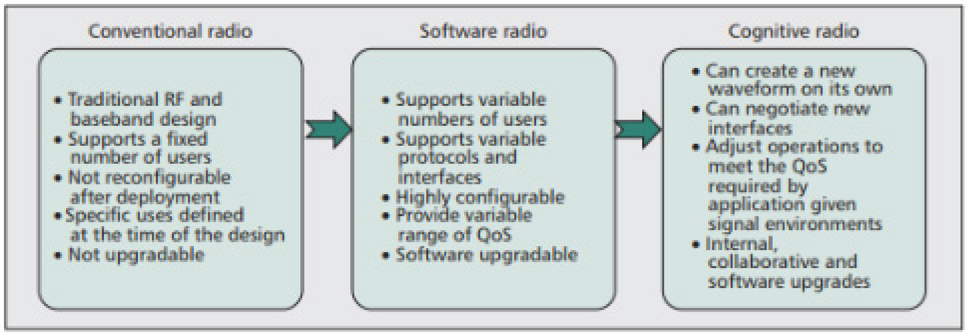


Figure 7. The evolution of tactical radios as three generations. Source: Elmasry (2013).

According to IEEE, SDRs are defined as "radio in which some or all of the physical layer functions are software-defined" (Jacobsmeyer, 2012, p. 1). Such functions as frequency, bandwidth, encryption, and modulation are controlled and configured using software code. The main components of SDRs are the Field-Programmable Gate Array (FPGA) and the A/D converter (Jacobsmeyer, 2012). FPGA is a semiconductor device that performs following conditional Configurable Logic Blocks (CBLs) that are programmable (XILINX, 2019). The FPGA algorithm is based on a logic gate with operators such as AND, XOR, etc. (Jacobsmeyer, 2012). The A/D converter is located between the SDR antenna and FPGA. When a signal is received, it is processed through the A/D converter, which will output the signal as a stream of data. This stream is then processed by FPGA algorithm and converted into the digital signal required for the application (Jacobsmeyer, 2012). Reverse steps are followed when transmitting a signal.

In 1997, the Pentagon launched Joint Tactical Radio System (JTRS) program with the vision of uniting communication systems across all services under JTRS organization umbrella (Kamal & Armantrout, 2013). The goal was to develop standardized communications requirements, translate them into appropriate acquisition requirements, and create a joint governing organization to oversee the acquisition and engineering processes (Anderson & Davis, 2006). Additionally, under the JTRS program, the military would transition from legacy radio communication to SDR systems. Although the program was shut down in 2012 due to budget constraints and failure to deliver promised interoperable and affordable advanced communication products to the warfighter, it led to establishment of the DoD Joint Tactical Networking Center (JTNC). JTNC serves as a single resource for open systems architecture, software code and other relevant information for the government and approved communications software developers (Joint Tactical Networking Center [JTNC], 2019). It also provides a comprehensive DoD communication waveform inventory including waveform's sponsors and subject matter experts (SMEs) for each system, software communication architecture, and serves as a technical advisor on wireless communications supporting the DoD (JTNC, 2019).

2. Modern Tactical Radios

Open system architecture provided by JTNC offered commercial companies an opportunity to engineer and develop communications systems that would adapt to warfighter requirements. Companies such as AT Communications, Harris Corporation, Thales Communications, and Persistent Systems are the leading industry partners that have been developing communication systems to meet those requirements. The Harris AN/PRC-163 (formerly RF-335M-STC) multi-channel handheld radio (Figure 8) is one of their many products used by the U.S. Army to exchange data between the operators and command centers and across the battlefield (Harris Corporation, 2019). This radio supports VHF/UHF line-of site, SATCOM, and MANET technology for data, voice and imagery (Harris Corporation, 2019).

Figure 8. Harris AN/PRC-163 multi-channel handheld radio. Source: Harris Corporations (2019).

Recently, the U.S. Army leadership expressed their desire to swiftly move from the hardware-centric legacy radios to more advanced SDRs and in 2018 committed to purchasing over 1,500 AN/PRC-163 units (Army Technology, 2018). The small dimensions of the radio of 6x3x2 inches and its weight of only 2.75 pounds alleviates the need for operators to carry heavy radio equipment even with optional accessories such as tether antenna mount, chargers, cables, etc. (Harris Corporation, 2019).

Similar to Harris AN/PRC-163 radios are Persistent Systems Man Portable Unit (MPU) 4 and MPU5 Wave Relay radio systems. Both MPU4 and MPU5 radios are peer-to-peer MANET devices supporting data, voice, and video applications. Persistent Systems (2017) claim these systems to be the most advanced, reliable, and secure MANET-compatible radios currently on the market. These Wave Relay radios are IPv4 and IPv6 compatible and adhere to the DoD encryption requirements (Persistent Systems, 2017). The upgrades to MPU5 include three RF antennas with 6W combined transmit power (MPU4 has only one RF antenna), 3x3 MIMO technology, increased throughput from 31 Mbps to over 100 Mbps, improved management system interface for a network administrator, and a Radio over IP (RoIP) function that allows integration with legacy radio systems (Persistent Systems, 2017).

Figure 9. Wave Relay radios. Source: Persistent Systems (2016a and 2017).

3. Other Commercial Solutions

Several years ago, a New-York based company goTenna Inc. developed a low-bandwidth, long-range goTenna Mesh radio device that worked with smartphones. The initial purpose on this radio was to provide text-messaging and GPS location-sharing capabilities between user in areas without cell coverage or WiFi. Such device was great for use while hiking or during other outdoor activities. As the popularity of goTenna Mesh grew, the company expanded their market to first responders with a more advanced goTenna Pro radio.

Figure 10. goTenna types. Source: goTenna (2019a).

GoTenna radio is a digital mesh-networking 5W (1W for goTenna Mesh) radio that supports VHF and UHF communications and provides text messaging, location, map information, emergency beacon, and other real-time situational awareness tools (goTenna, 2019a). This system works with Android and iOS compatible with goTenna Pro Team Awareness app, requires no preexisting infrastructure, and supports PKI Top Security (TS) level encryption (goTenna, 2019a). In 2018, goTenna conducted experiments with the Royal Navy and Royal Marines to demonstrate goTenna Pro capabilities in Humanitarian Assistance/Disaster Relief (HA/DR) and Surveillance and Reconnaissance scenarios (Davies, 2018). According to the after-action report, goTenna performed successfully in a network of three hops transmitting and receiving small data packets supporting position location information (PLI) refresh every 30 to 180 seconds and chat message exchange (Davies, 2018). Although the DoD currently does not utilize any of the goTenna Inc. products, we explore their possible application for self-moving tactical networks.

D. UNMANNED VEHICLES

When discussing unmanned systems, there are many different definitions for the term unmanned, which can sometimes be interchanged with autonomous or self-moving in academia and the civilian sector. We sought three separate definition sources to compare results. The Oxford English Dictionary (n. d.) defines *unmanned* as “not having or needing a crew or staff.” Merriam Webster Dictionary (n. d.) states that *autonomous* is “undertaken or carried on without outside control.” And finally, Dictionary.com (n. d.) describes *self-moving* as “capable of moving without an external agency.” This demonstrates the confusion with each terms and how they have often times been used interchangeably in research and commentary.

In the context of this research, our exploration of unmanned technology refers to any technology that allows the vehicle or system to be controlled remotely, without humans physically interacting with the device. This type of remote control can be done via joystick controller operation over radio waves, pre-programmable or on-the-spot programmable waypoints delivered via mesh networks, or artificially intelligent operating systems that make decisions to move on their own based on a pre-existing ruleset. We explored all available unmanned technology available for use or observation at the time our research was being conducted.

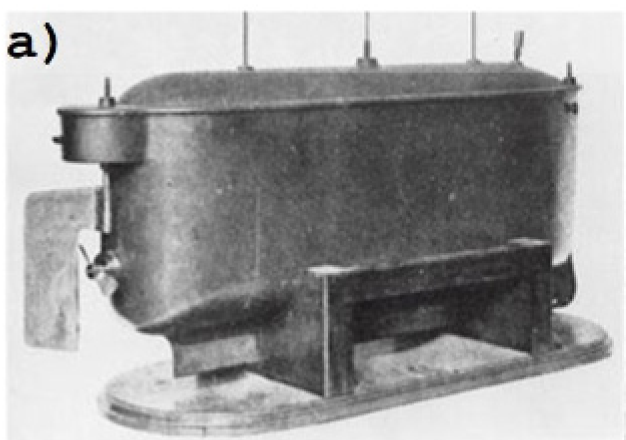


Figure 11. Telsa’s Teleautomaton. Source: Czapla and Wrona (2013).

Unmanned vehicles (UV) have been in existence for well over a century, with the first known example being a remotely controlled boat creating by Nikola Tesla in 1898, which the military had no interest in (Czapla & Wrona, 2013). Much to Tesla’s chagrin, unmanned platforms were not seriously considered for military applications until over 20 years later and only as a means to deliver explosives to the enemy (Czapla & Wrona, 2013). These vehicles were most often designed as tanks, developed in the 1930s as a strategy response to operations in the First World War (Czapla & Wrona, 2013).

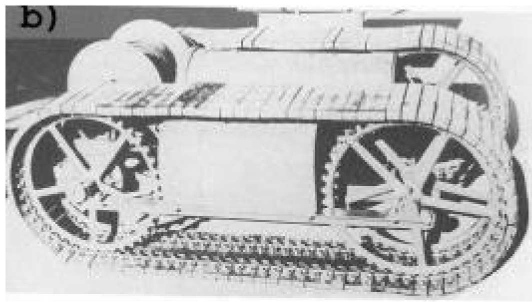


Figure 12. Wikesham's land torpedo. Source: Czapla and Wrona (2013).

1. Ground Domain

The U.S. military's first real venture into the development of Unmanned Ground Vehicles (UGV) occurred when Stanford Research Institute, funded by DARPA, developed Shakey, a boxlike computer structure with wheels and various sensors that had a limited set of commands and actions it could execute (Gage, 1995). Shakey was also the first robot that was "smart" enough, via its artificially intelligent programming, to make decisions on how to navigate obstacles on its own (DARPA, 2019a). UGVs now come in all shapes and sizes, for a variety of civilian and military missions.

Figure 13. Shakey the Robot. Source: DARPA (2019a).

Much of the military's research in unmanned ground systems has laid with the U.S. Army. The DoD currently employs several types UGV for various tasks, including mine and Improvised Explosive Devices (IED) detection, supply mule carriers, unmanned tanks, and unmanned convoy vehicles (Verdict Media Limited, 2019). In 2005, DARPA invented the first supply-carrying robot, meant to carry supplies for troops in the field (DARPA, 2019a). These types of robots are still used today and are often referred to as *supply* or *pack mules*.

Figure 14. DARPA's Big Dog. Source: DARPA (2019c).

Some of the more widely known UGVs are the National Aeronautical and Space Administration (NASA) Mars Rovers, built to explore the Martian planet's surface (Gage, 1995). These small movers, traveling up to 10 km per day, started being built in the 1970's, successfully landed on the planet surface for the first time in 1996, and have accomplishment a plethora of valuable Mars terrain mapping and sampling information since that time (NASA Mars Exploration Program, 2019). Today, many UGV have multi-terrain capabilities due to the lessons learned from extensive research required to enable the rover to navigate uneven and uncertain terrain conditions.

Figure 15. Mars Curiosity rover selfie. Source: NASA (2019).

2. Air Domain

Unmanned Aerial Vehicles (UAV) are the most prevalent form of unmanned technology in the U.S. Military and have been utilized since 1917, with the advent of the first feasible unmanned aircraft (Gertler, 2012). The UAV was called the Hewitt-Sperry Automatic Airplane and gained the U.S. military's interest, but ultimately, was wrought with accuracy and technical issues (Dalamagkidis, 2015). Although radio control had been developed in the late 1900's by Telsa, the attraction of UAVs did not rise again until the commercial industry developed remote-controlled plane technology and proved the UAV could be controlled with accuracy for military operations (Dalamagkidis, 2015).

Today, every service owns several versions of unmanned aerial technology, with dimensions ranging from insect-sized to commercial airline-sized (Gerlter, 2012). There are many ways in which to classify UAVs, including basic shape and size, energy consumption, operational altitude, ground collision or midair risk, etc. (Dalamagkidis, 2015). Table 1 is a basic classification chart based on maximum takeoff weight, commonly referred to as MTOW. Figure 16 shows the variety of UAV that the military has been utilizing during the past six years.

Table 1. UAV classification by size. Source: Dalamagkidis (2015).

	Mass (kg)	Range (km)	Flight alt. (m)	Endurance (h)
Micro	<5	<10	250	1
Mini	<20/25/30/150[a]	<10	150/250/300	<2
Tactical				
Close range (CR)	25–150	10–30	3,000	2–4
Short range (SR)	50–250	30–70	3,000	3–6
Medium range (MR)	150–500	70–200	5,000	6–10
MR endurance (MRE)	500–1,500	>500	8,000	10–18
Low altitude deep penetration (LADP)	250–2,500	>250	50–9,000	0.5–1
Low altitude long endurance (LALE)	15–25	>500	3,000	>24
Medium altitude long endurance (MALE)	1,000–1,500	>500	3,000	24–48
Strategic				
High altitude long endurance (HALE)	2,500–5,000	>2,000	20,000	24–48
Stratospheric (Strato)	>2,500	>2,000	>20,000	>48
Exo-stratospheric (EXO)	TBD	TBD	>30,500	TBD
Special task				
Unmanned combat AV (UCAV)	>1,000	1,500	12,000	2
Lethal (LET)	TBD	300	4,000	3–4
Decoys (DEC)	150–250	0–500	50–5,000	<4

[a]Varies with national legal restrictions

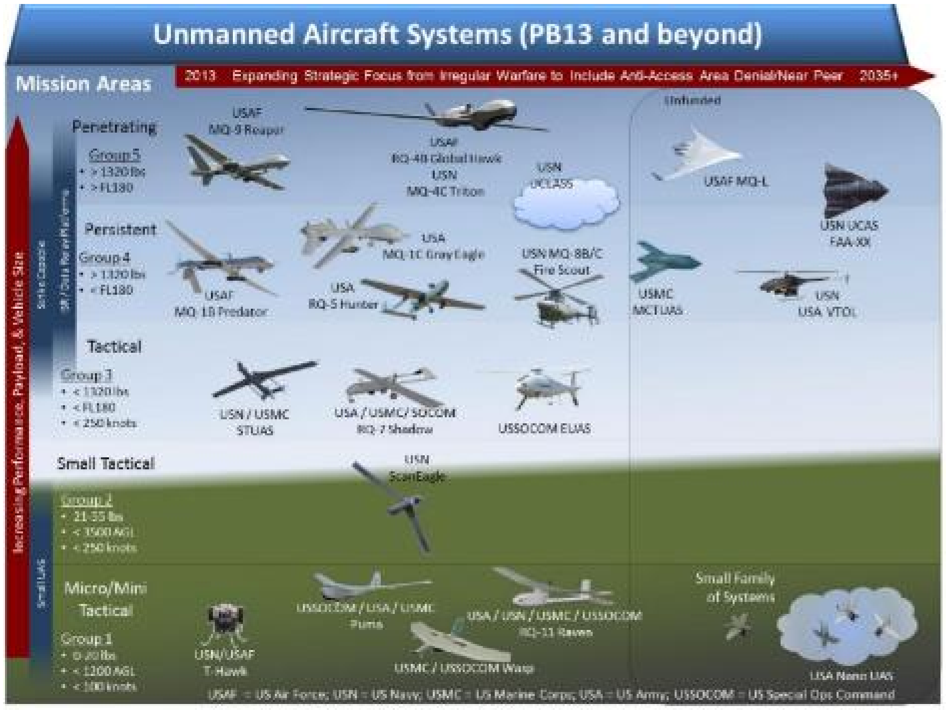


Figure 16. U.S. military unmanned aircraft systems diagram. Source: Shaw (2016).

3. Maritime Domain

Unmanned surface vessels (USV), unmanned underwater vehicles (UUV), and amphibious components are widely used by the academic research communities for oceanographic studies, but have great implications for military operations as well. This group of aquatic vehicles are also referred to Unmanned Maritime Vehicles (UMV) and have gained popularity within the military ranks over the last 20 years (*Progressive Digital Media Defense News*, 2014). A discussed earlier in the chapter, Tesla developed the very first UMV, the Teleautomaton. Today these systems are being utilized for various type of missions, from oceanographic studies, mine-hunting, intelligence gathering, and decoys, to explosive payload delivery (DeLuca, DeWeese, Kenney, Martin, Schmid, Tarraf, & Whitmore, 2019). NPS currently operates two SeaFox USV and a Remus UUV that have been involved in several network communications experiments (Hurban, 2012). We gained first-hand knowledge of the vehicles while participating in NPS's Multi-Thread

Experiment in San Clemente Island, CA, which will be further discussed during the discovery phase of the thesis.

Figure 17. U.S. Navy UMV. Source: Navy (2007).

4. Unmanned Service and Repair Vehicles

UxV whose primary purpose is to maintenance and repair other systems is a fairly new development in the unmanned domain. DARPA has launched a Robotic Servicing of Geosynchronous Satellites (RSGS) program and is currently seeking bids from vendors to create a Robotic Servicing Vehicle (RSV) that can inspect and service satellites in geosynchronous orbit (DARPA, 2019b). These RSVs could dramatically change the longevity of existing satellites, expand spacecraft designs, lower manufacturing costs, and extend satellite reliability (DARPA, 2016). One major component of the RSV will be a robotic arm that would be able to perform multiple generic and specific mission tasks, with the ability to work on existing satellites not originally designed for docking (DARPA, 2016).

These types of unmanned vehicles could prove useful in every domain, such as underwater repair to subsurface and surface vessels or stationary structures, robotic refueling or repair of surface vessels, repair, realignment, or refueling of ground vehicles, and mid-air refueling or repair of aircraft.

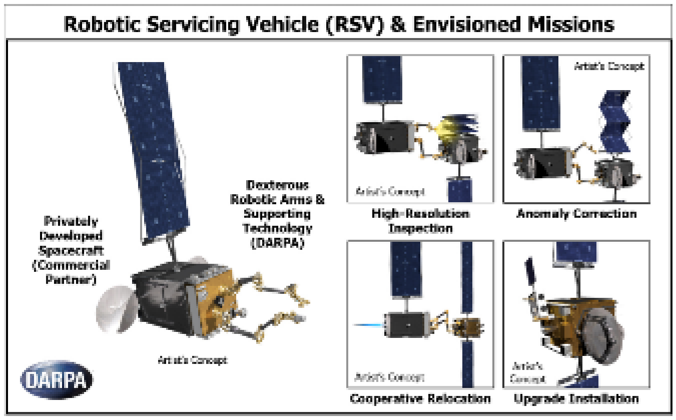


Figure 18. DARPA's RSV concept. Source: DARPA (2016).

E. PREVIOUS RESEARCH

This section covers the previous research on the individual components that informs our thesis research. One of the main sources of research was that of NPS's Center for Network Innovation and Experimentation (CENETIX). Dr. Alex Bordetsky, head of CENETIX, and Eugene Bourakov, lead CENETIX scientist, conducted many experiments that enhanced our understanding of mesh network operations, radio control, and unmanned vehicle capabilities.

1. Utilizing Directional Antennas for Ad Hoc Networking (UDAAN)

Research into mobile ad hoc networks gained momentum with development of SDRs supporting MANET architecture. Besides having the best radio for the network, the type of antenna systems can either enhance or hinder network performance. Ramanathan, Redi, Santivanez, Wiggins, and Polit (2005) suggest that to achieve maximum transmission range while maintaining network stability, it is best to use directional antennas between nodes regardless of the complexity of the network. They presented a complete solution called Utilizing Directional Antennas for Ad Hoc Networking (UDAAN) that could be employed in a variety of scenarios and designed an experiment to prove the superiority of directional antennas for ad hoc networks (Ramanathan et al., 2005). The field test consisted of 20 ground vehicles (Figure 19) and each vehicle was outfitted with one 2.4 GHz radio, one omnidirectional antenna with 6 dBi gain, and four directional antennas with 6 dBi gain (Ramanathan et al., 2005).

Figure 19. UDAAN ground node set up. Source: Ramanathan et al. (2005).

The test was conducted over a three-hour period during which the ground nodes were moving randomly with respect to one another. Network performance data collected during the test mirrored the lab test that was conducted prior to the field test. It indicated that UDAAN network parameters were much better than those of omnidirectional antennas—network delays were shorter and throughput capacity was higher (Ramanathan et al., 2005). This experiment showed that although omnidirectional antenna systems are more convenient to use for networks with multiple nodes with consideration of the amount of equipment required, it is much better to use directional antennas to achieve higher network performance.

2. Using Commercial Satellites and UUV Technology to Solve Maritime Detection and Interdiction Challenges through Self-Forming Mesh Networks

This research was a multi-phase experiment conducted throughout 2018 at NPS by Bordetsky, Bourakov, Moltz, and Mullins (2018). The results proved that UUV or divers underwater could transmit and receive complex data sets while underwater, through a mesh network (Bordetsky et al., 2018). The biggest takeaway for our thesis research was the design and perfection of directional antenna on the RMP-400 UGV, which increased mesh network throughput by at least 300% and ensured high quality radar data between the diver and TOC (Bordetsky et al., 2018).

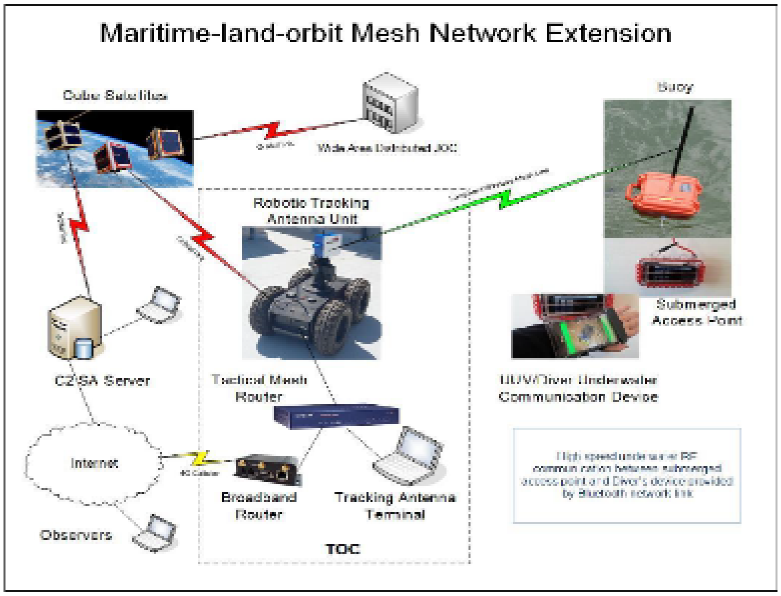


Figure 20. Maritime mesh networking diagram. Source: Bordetsky et al. (2018).

3. Testbed for Tactical Networking and Collaboration

Bordetsky and Netzer explain the Tactical Network Testbed (TNT) experiments that commenced at NPS in 2002 and lead to many successful experiments that integrated networks, sensors, UxV, and personnel into moving, tactical networks. This research was pursued when it was realized that many situational awareness shortfalls existed for warfighters in tactical communications situations, especially in the SOCOM field (Bordetsky & Netzer, 2010).

Several Maritime Interdiction Operation (MIO) experiments were conducted involving academic, civil, and foreign partners, in exploring the best way to extend communications while searching large vessel cargos for nuclear radiation threats in high traffic ports (Bordetsky & Netzer, 2010). The main locations for these tests were the San Francisco Bay and Hampton Roads areas but also included sites across the world for information sharing (Bordetsky & Netzer, 2010). These experiments demonstrated using mesh wireless networks for communications between the warfighter and reach back to the respective TOC and nuclear radiation experts dispersed across various geographic areas, as depicted in Figure (21) (Bordetsky & Netzer, 2010). Detection and identification of nuclear radiation material was able to be shared across multiple geographic regions within four minutes (Bordetsky & Netzer, 2010). Better situational awareness was also established due to the boarding vessels and other small craft involved in the experiments being linked together with a self-forming mesh network (Bordetsky & Netzer, 2010).

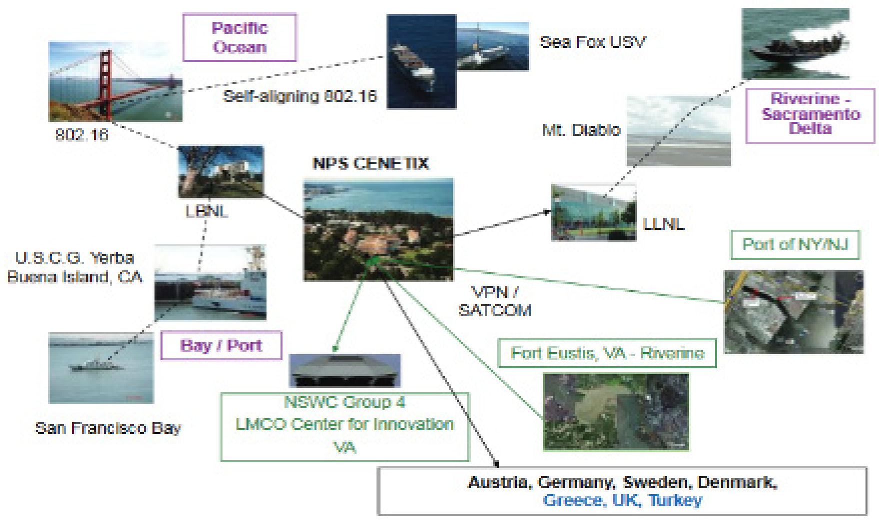


Figure 21. MIO testbed segment. Source: Bordetsky and Netzer (2018).

4. Network on Target: Remotely Configured Adaptive Tactical Networks

This experiment started out with the identification of poor video quality of various UxV when using an Orthogonal Frequency Division Multiplexing (OFDM) 802.16 network backbone. Bordetsky and Bourakov (2006) resolved the poor video quality by introducing Self-Aligning OFDM (SAOFDM), which used a newly developed computer-controlled pan-tilt unit to align the antennas based on control link quality and GPS positions. After implementing SAOFDM, a UAV was integrated into the experiment to further extend the communications range and evaluate integration techniques for other studies involving MIO and high value target searches (Bordetsky & Bourakov, 2006).

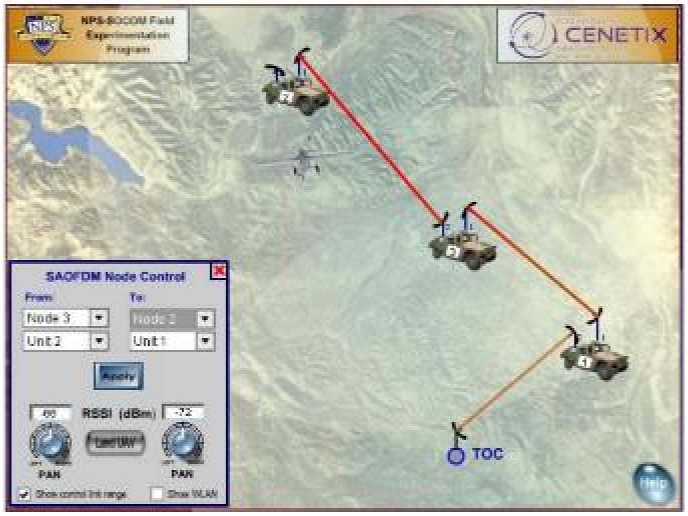


Figure 22. SAOFDM network diagram extended by UAV node. Source: Bordetsky and Bourakov (2006).

III. EXPERIMENT DESIGN

This chapter includes the methodology and various phases of our research from design to field testing.

During Phase 0, we formulated our thesis concept based on our involvement with the 2017 NPS Multi-Thread Experiment (MTX) and identification of warfighter communication gaps. We identified current practical and theoretical issues and limitations of rapidly deployable communications as we examined previous research.

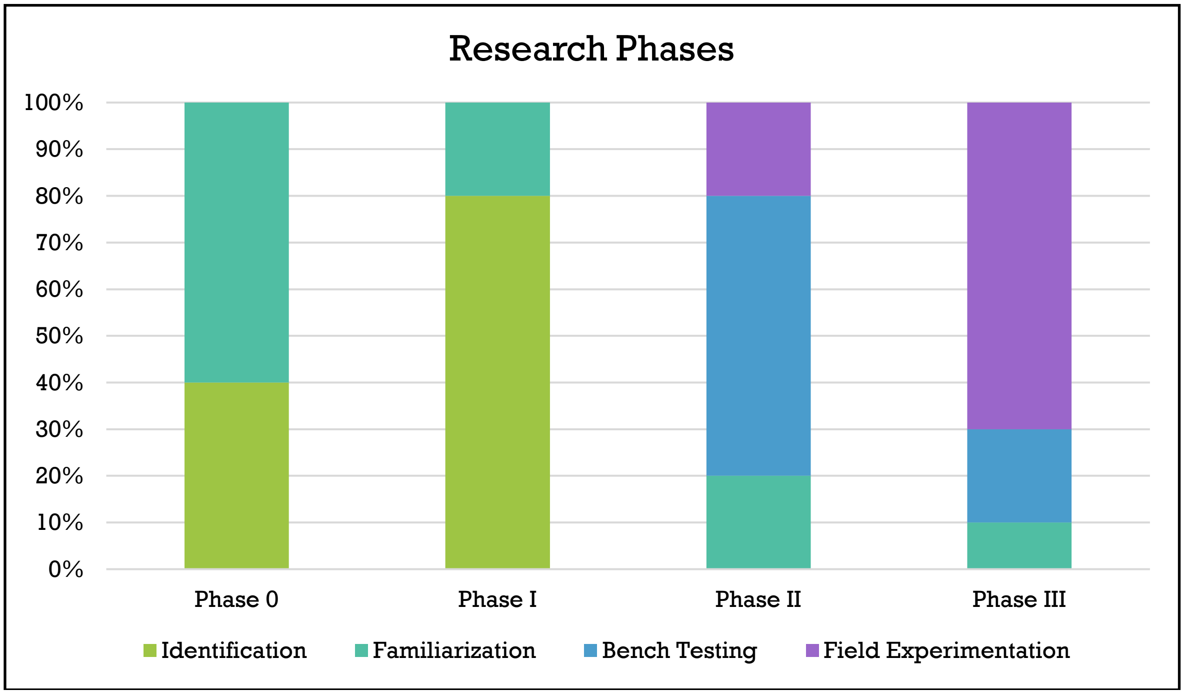
Phase I commenced with our search for equipment. NPS has limited access to unmanned systems and only a small variety of communications equipment so we sought out other academic, military, and civilian partners to observe and evaluate their equipment inventory. We spoke with various subject-matter-experts and reviewed specifications for their equipment, then selected from among available systems that were compatible with our research questions.

In Phase II, we conducted bench testing to verify the capabilities and limitations of our selected equipment. This consisted of multiple experiments in various locations with the goal of pushing the equipment to its limits and evaluating overall network performance.

Phase III consisted of two major field experiments on two UGV systems to confirm our proof of concept and capture basic network and operating parameters.

Table 2 is a graphical representation of experiment design during each of the four phases.

Table 2. Research phase development



A. PHASE 0 - IDENTIFICATION

This phase commenced during our participation in the 2017 NPS Multi-Thread Experiment (MTX) in San Clemente Island, CA.

1. Concept Creation - Multi-Thread Experiment

In November of 2017, we participated in the NPS Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) sponsored MTX, located in San Clemente Island (SCI), CA. Our primary role for the experiment was supporting NPS CENETIX with network administration in the TOC. We monitored network performance via multiple software applications, troubleshot connectivity issues, realigned stationary nodes throughout the island, and observed UxV operations and communication links.

SCI is the most southern Channel Island in California, roughly 68 nautical miles west of San Diego. The island is 21nm long and roughly 4.5 nautical miles at its widest point (San Clemente Island, 2019a). The island is owned by the U.S. Navy and is home to the San Clemente Island Range Complex (SCIRC), managed by Southern California Offshore Range (SCORE) command at Naval Air Station North Island, CA (San Clemente Island, 2019b). Due to the nature of the island's location, U.S. government ownership, and the ability to utilize the various ranges for highly specialized testing, this site was an ideal choice for conducting MTX.

The MTX scenario designated SCI as *country orange island,* in which hostile forces are suspected of smuggle radiological material onto the island in hopes of selling it to *country red* unfriendly forces. *Country red* is believed to have assets in place on *country orange island*, performing clandestine mining operations. A Sea, Air, Land Team (SEAL) is in the operating area and is tasked with a search and recovery mission. The SEALs need in depth Intelligence, Surveillance, and Reconnaissance (ISR) to perform their mission and will employ unmanned aerial, surface, and subsurface assets to maintain a low visibility and involve minimal U.S. forces.

2. Issue Identification

During MTX, it was necessary to network operators to go into the field frequently to manually adjust the communication nodes across the island on multiple occasions, for a variety of reasons. In a real mission, the network technicians who went into the field to adjust communications nodes would have been at great risk for detection by enemy forces, hostile fire, or mission failure. We developed the following research goals based on the problems observed:

1. Reduce the risk to network operators when establishing and maintaining tactical network communications in austere environments.

2. Identify unmanned vehicles and equipment that can perform selected network configuration functions, while allowing network operators to direct, observe, and maintain situational the network from a safe standoff distance.

B. PHASE I – REQUIREMENTS AND EQUIPMENT SELECTION

In this phase, we visited several organizations involved in research and development of unmanned systems in order to select unmanned vehicles and communication systems that we deemed suitable to support our self-moving tactical network.

1. Research Partners

We sought out industry and government partners in an effort to better understand current unmanned technology and establish collaboration opportunities for our research and future CENETIX experiments.

a. Equinox Innovative Systems

In August 2018, we attended an Artificial Intelligence (AI) & Autonomy for Humanitarian Assistance & Disaster Relief (HA/DR) Workshop co-hosted by the Office of Naval Research (ONR) at Carnegie Mellon University (CMU) in Pittsburg, PA. During this workshop, representatives from the academia, industry, government and first responders shared their ideas and experiences and collaborated in efforts to bring more AI and autonomy capabilities in support of HA/DR operations. We interacted with one of the industry partners in attendance, Equinox Innovative Systems, and learned about their Falcon tethered drone. Falcon is a communication and optics platform that weighs approximately 10 lbs. and is connected to a 150-meter tether that could be mounted to any vehicle to provide communications and situational awareness data (Equinox Innovative Systems, 2017). It is designed to host various of communication devices such as peer-to-peer, mesh, WiFi, and cellular devices as well as visual, thermal, and ultraviolet (UV) cameras and hover without landing for over eight hours (Equinox Innovative Systems, 2017). We initiated a cooperative research and development agreement (CRADA) between NPS and Equinox Innovative Systems but the CRADA was not finalized in time in order for us to incorporate tethered drones into our experiments.

b. *Space and Naval Warfare Systems Command (SPAWAR)*

NPS CENETIX has long been collaborating with the Space and Naval Warfare Systems Command (SPAWAR) during events such as MTX and Joint Interagency Field Experimentation (JIFX). Shortly after MTX, Dr. Bordetsky shared with them our thesis proposal to include unmanned ground vehicles as moving nodes. Since SPAWAR has been focusing on air and maritime domains, they offered a few older unmanned ground vehicles for our use. We were able to obtain four Endeavor Robotics Packbot unmanned ground vehicles to NPS. Although this platform is somewhat outdated, we studied its applicability to our architecture.

c. *Navy Research Laboratory, Washington, D.C.*

We initially met our Navy Research Laboratory (NRL) contact at the Carnegie Mellon AI HA/DR conference mentioned above. After the conference, we visited NRL to see what testing facilities they offered and if there were any unmanned vehicles that might meet our research needs. Our visit to NRL in Washington, D.C. occurred in December 2018. During this time, we were able to tour the testing facilities, observe their unmanned systems, and discuss our project with subject-matter-experts in various fields. Their tropical testing bay was complete with lush, tropical foliage and temperature-controlled humidity, perfect for testing equipment in a hot, humid environment with lots of LOS complications. They had a desert bay with arid heat and sand, which could be used to test how well unmanned systems and equipment faired in those conditions. They also had an aerial bay in which unmanned aerial systems could be tested and monitored, via nodes covering the entire bay. And lastly, they had a swimming pool that could be used to test unmanned surface and subsurface vehicles and communications equipment. Unfortunately for us, most of NRL's current work rests with various UAV and UUV systems, which did not fit into our thesis research. They did have a few older small platform UGV and tether-able quad-copter UAV systems but all of them were end-of-life and no longer fully functioning. We did find interest in a low altitude mini-dirigible that could be used to extend LOS communications in tactical scenarios, but the propulsion system is currently too delicate for use in a non-lab environment. We also found interest in some of their communications equipment testing, specifically an NRL designed and manufactured SDR and phased array antenna. The SDR and antenna are not currently on a funded project and the SMEs were not able to dedicate their full attention to the development of these systems so it was not something we could utilize for field testing at this time.

d. Ben Gurion University of the Negev, Israel

Ben Gurion University (BGU) of the Negev has a Laboratory for Autonomous Research (LASR) that created an Intelligent Vehicle Operator (IVO) system which seemed to be a suitable concept for our research. We contacted the University and set up a teleconference for collaboration. After learning more about the IVO system, we decided it would be an extremely beneficial addition to our thesis research and we needed to experiment with it in person. After designing an experiment, in collaboration with LASR, we flew to Israel in April of 2019 to meet with the BGU LASR team and see IVO in action. BGU became our most successful contacts, as their system was ready and available to be field tested with our communications equipment. A detailed description of the experiment will be detailed later in this chapter.

2. Unmanned Vehicle Selection Process

Our original intent was to experiment with a tactical network configuration using a fully autonomous ground vehicle. We quickly found out that none of our research partners had such a vehicle and companies that did have a fully autonomous vehicles were utilizing programming algorithms that met their specific design needs. There was not a one-configuration-fits-all vehicle that could be repurposed for our experiment. Due to these issues, we chose vehicles based on the following factors:

- Availability- can it currently be used in field experiments.
- Payload Capacity- minimum carrying capability 5 pounds, based on our selected communications and sensor equipment.
- Range- minimum 8-mile distance, based on average remote terrain operating areas for special operations.

- User Control Unit- vehicle has the ability to be controlled from a long-range distance to keep network operators at a safe stand-off distance.
- Speed- minimum of 10 miles per hour to rapidly deploy and adjust the network for tactical C2.
- Detection Footprint- how detectable is the vehicle noise signature and visual profile.

a. Segway Robotics Mobility Platform (RMP)-400

The bulk of our UGV testing occurred with the RMP-400, as it is readily available to CENETIX students at NPS. RMP-400 consists of two Segway base components housed together in a metal rectangular structure. Each Segway base component has two rugged terrain tires. It is powered by four lithium ion batteries with an option to charge via portable external batteries. RMP-400 vehicles can use Controller Area Network (CAN), Universal Serial Bus (USB), or User Datagram Protocol (UDP) interfaces for control, but the actual controller interface mechanism must be designed by the consumer. The CAN serial bus is a real-time asynchronous collision-detection broadcast that sends and receives data messages at speeds of up to 1megabit per second for in-vehicle networks (Bril, Burns, Davis, & Lukkien, 2007). CAN is important for use in vehicles because the continuous communication link ensures that if connectivity is lost, the vehicle will stop rather than continuing on with the last received command and becoming an uncontrolled safety hazard. Eugene Bourakov designed an upper level control application on an Android device that send commands to control the wheel speed and direction via the CAN bus. An MPU4 radio with WiFi-enabled hotspot is plugged into the RMP's Ethernet port and allows commands to be transmitted from the android phone to the RMP-400. RMP-400 can also be controlled via additional radio communication nodes, enabling the operator to be at a greater distance from the vehicle while operating it. This is an advantage for rapidly deployable tactical network configuration.

The user can control the RMP-400 by operating the Android device in the same manner a joystick would be used. The speed is controlled by the holding the cell phone in a vertical positon, with the application open, and tilting the phone in a forward and backwards motion between a flat, horizontal position and vertical position. Turning directions are controlled by moving the phone to the left or right. Figure (23) demonstrates vehicle speed control interface on the Android phone platform and Figure (24) demonstrates vehicle maneuvering control on the Android phone platform.

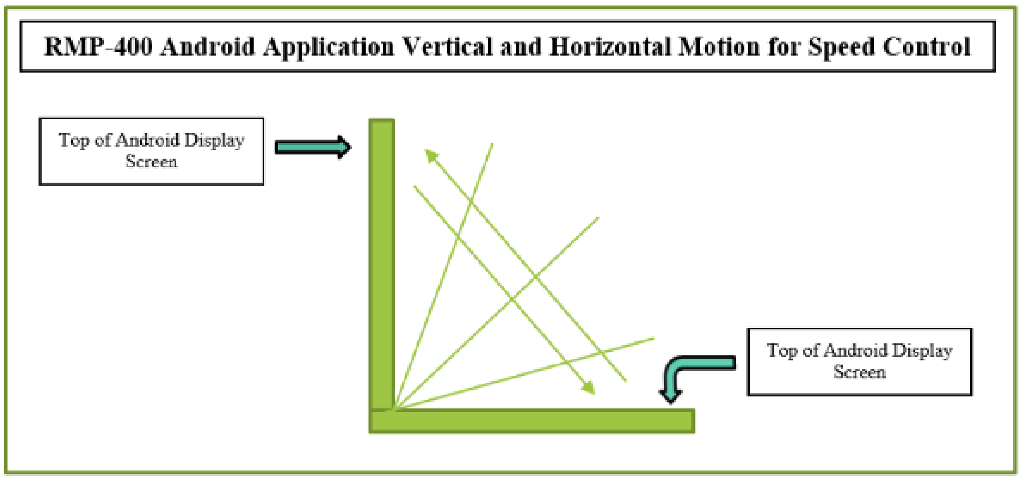


Figure 23. RMP-400 Android application vertical and horizontal motion for speed control

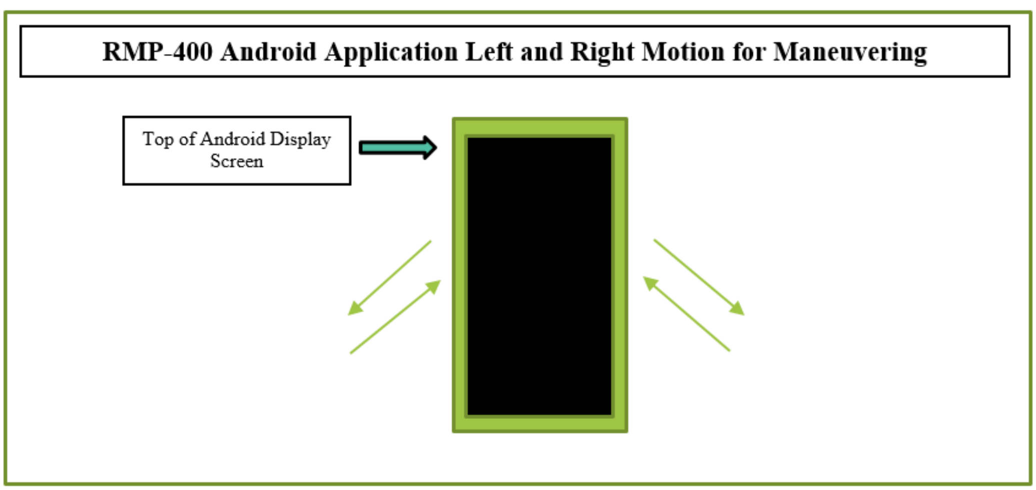


Figure 24. RMP-400 Android application right and left motion for maneuvering

Figure 25. RMP-400 control interface Android application

Figure 26. RMP-400 with directional antenna attachment

b. Endeavor Robotics Packbot

The Endeavor Robotics Packbot is an all-terrain, all weather UGV utilized in many military operations, to include IED disposal (Verdict Media Limited, 2019). The Packbot has a top speed of 5.6 mph and run-time of 4 hours for onboard batteries, making it less desirable from a speed and range capacity. The most attractive feature on this vehicle is the extendable arm, which can grasp items and carry a load of 10 lb. when fully extended or 30 lb. when in a close-in position. It is also able to climb stairs, which we were able to observe firsthand at a JIFX in Camp Roberts, CA. Although it did successfully navigate the stairs, it fell down several times in the process and moved extremely slow and delicately. Additionally, the operator had to stand within very close range of the device, making it unsuitable for use in our thesis experimentation.

Figure 27. Endeavor Packbot. Source: Verdict Media Limited (2019).

c. Robo-team Individual Robotic Intelligent System (IRIS)

The Robo-team IRIS is a very small, lightweight, all-weather, all-terrain UGV with two onboard cameras (Robo-team, 2016). At only 3.6 pounds, it can be hand-carried by tactical teams and thrown into areas where additional surveillance is needed. Control and video feed is done through a ruggedized tablet so the operator can remain at a safe distance from whatever the IRIS is investigating (Robo-team, 2016). Unfortunately, due to its compact size it can only carry a payload of 2.2 pounds, which could not support the type of tactical communications needed for network configuration during SPECWAR missions. The speed is also a hindrance, as it can only travel 3 mph, which would be much to slow to use in network construction or adjustment.

Figure 28. Robo-team IRIS. Source: Robo-team (2019).

d. Ben Gurion University (BGU) Intelligent Vehicle Operator (IVO)

The IVO was developed at Israel's Ben Gurion University of the Negev Laboratory for Autonomous Robotics (LASR). IVO is basically a *robot chauffeur*, weighting roughly 44 pounds and able to be installed in any vehicle that is designed for anthropomorphic operation proportions. Installation of IVO takes between 5 and 15 minutes. Because IVO fits into any human-drivable vehicle, the payload capacity and speed options are only limited by the vehicle size and maximum speed. It operates on internal batteries with optional additional batteries that can be carried inside the respective vehicle. The system can be controlled via several options: full autonomy, onboard controller, or remote control.

Autonomous control is done through raw video feed, which BGU has programmed high-level algorithms to help IVO make driving decisions with tools like roadway detection, obstacle avoidance, and object classification (Guterman & Yechiel, 2017). Autonomous operations are still being perfected as new versions of IVO are produced.

Onboard control is done via a person sitting in the passenger seat of the vehicle with a joystick connected to IVO. A laptop with IVO's video and system feeds is not required because the operator is in the car, seeing the same scene that IVO is capturing.

Remote control is performed via joystick connected to a laptop. The laptop has video and system streaming from IVO because it is connected via ethernet to a radio for long-range communication. An additional radio is placed on the IVO-driven vehicle with an ethernet cable hooked into IVO for communication with the remote operator.

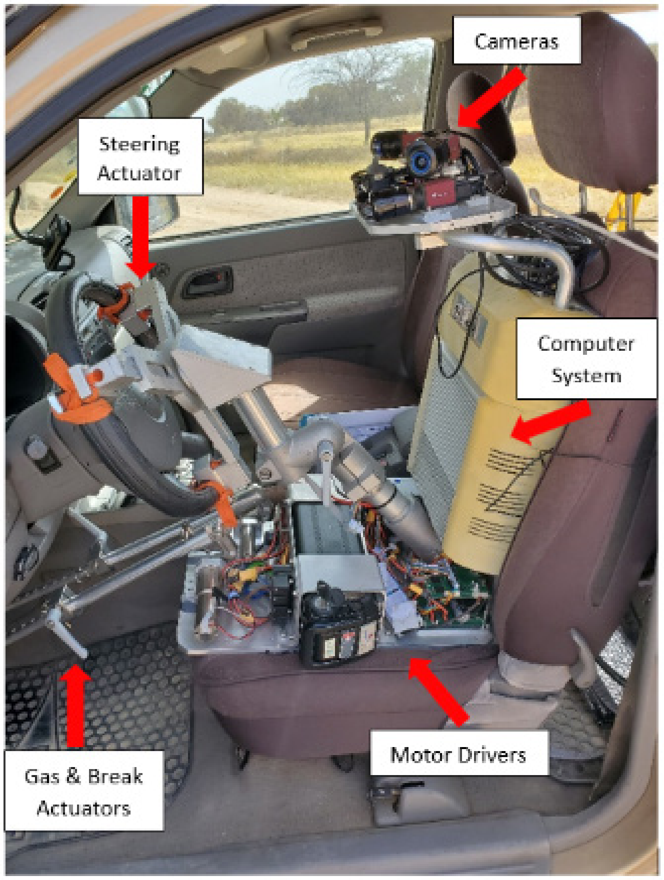


Figure 29. BGR IVO components

IVO has great potential for use in civilian and military applications. For military use, its major appeal is that it can turn any military vehicle into an autonomous or remotely controlled vehicle. In addition, they are fairly inexpensive when compared with other autonomous solutions. Possible drawbacks could arise with using larger vehicles for tactical missions, as it increases the detection footprint when operated in covert or sensitive missions. IVO could also be used for long-haul logistics as well, such as cargo or personnel transports.

Table 3. UGV characteristics comparison

VEHICLE	WEIGHT	PAYLOAD CAPACITY	MAXIMUM SPEED	RANGE	OPERATOR CONTROL UNIT	EXTRAS
Segway RMP-400	~240lb	400lb, evenly distributed	18 mph	10-15 miles Approx. 5 hours run-time	User built Android Application Remote control via radio nodes	Flat large surface area allows for nearly unlimited payload design Not water resistant
Endeavor Packbot	~31.6lb platform Arm is 21.6lb	10lb arm lift at full extension 30 lb arm lift at close-in position	5.8 mph	4 hours on two batteries 8 hours on four batteries	Android Multi-Robot Control System	Water resistant up to 3ft deep All weather, All terrain 4 onboard cameras
Robo-Team IRIS	~3.6 lb	2.2 lb	3 mph	700 ft 1-2 hours run-time	Ruggedized Tablet, encrypted IP	All weather, All terrain 2 Onboard Cameras Throw-able
BGU IVO	~44 lb	Unlimited, based on vehicle	Unlimited, based on vehicle	5 hours per battery	Onboard Controller Remote control via radio nodes Autonomous mode	Fits into any human-drivable vehicle

Adapted from Endeavor Robotics (2019); Guterman and Yechiel (2017); Robo-team (2016); and Segway (2019).

3. Communication Equipment Selection Process

Based on the technology review and previous CENETIX experiments, we selected the communication equipment suitable for our research. We examined and compared the radio systems that could be implemented for unmanned vehicle control and network data link and the antenna systems that would support our network architecture.

a. Radio Equipment

During MTX, we used Persistent Systems MPU4 Wave Relay as network nodes and Wave Relay quad radios as the backbone and relay node. Wave Relay quad radio router has four radio interfaces, five 10/100 Mbps Ethernet ports, and two serial ports and integrates with any Wave Relay radio for peer-to-peer connectivity (Persistent Systems, 2016b). Additionally, the ragged design and hardened case allow these radios to be safely used in hard environments (Figure 30). The quad radios were connected to omnidirectional antennas and seamlessly worked with MPU4 network transmitting data, voice and video stream. We decided to use this Wave Relay quad radios for out thesis due to familiarity with the equipment, its ease of use, and availability.

Figure 30. Wave Relay quad radio router. Source: Persistent Systems (2016b).

We at first decided to use the same radio equipment in our experiments as we did in MTX. However, shortly after MTX, CENETIX received several MPU5 radios in addition to the MPU4 that we already had. This prompted us to compare the capabilities and limitations of both MPU4 and MPU5 and chose the radio that better fits our requirements. One big advantage of MPU5 is its 6W transmit power vice 2W of MPU4. MPU5 provides a higher throughput of data and operates under MIMO technique. Also, the manufacture’s specifications claim the maximum distance between two unobstructed radios is 130 miles (Persistent Systems, 2017). Since MPU5 radios seemed to have multiple upgrades to MPU4, we elected to use them in our thesis.

In search of radio systems we could use in our network architecture, we also researched other commercial of the shelf (COTS) systems such as Harris AN/PRC-163 and TrellisWare radios. Unfortunately, we were unable to acquire any AN/PRC-163 units for our experimentation. TrellisWare products were used in previous CENETIX experiments.

The two TrellisWare we considered were TW-950 TSM SHADOW and TW-400 TSM CUB that are very similar in design and specifications (Figure 31).

Figure 31. TrellisWare TW-950 TSM SHADOW radio. Source: TrellisWare (2019).

TW-950 TSM SHADOW and TW-400 TSM CUB radios SDRs with transmit power of up to 2W designed for mobile ad-hoc networking providing simultaneous data, voice, video, and PLI (TrellisWare, 2019). They integrate with Android devices and have a point-to-point data rate of up to 16 Mbps (TrellisWare, 2019). A network of these radios can support over 200 nodes on a single channel with a line-of-sight range of over 26 miles. (TrellisWare, 2019). These radios seemed like a good fit for our tactical network; however, according to TrellisWare (2019), these radios can only support up to 8 hops which makes the network not as flexible and scalable as a network of Persistent Systems radios. Additionally, the radios are only interoperable with other TrellisWare's waveform technology and would not integrate with any other types of radios – the constraints we decided to avoid.

Table 4. Radio specification comparison

Radio	Weight (radio only)	Transmit Power	Data Rate	Max No of Hops	Range	Battery Life	Encryption
Harris AN/PRC-163	18 oz	5 W	16 Mbps	Unlimited	26 mi LOS	n/a	Denali-based Type-1 Suite A/B
TrellisWare TW-950 TSM Shadow	11.3 oz	2 W	16 Mbps	8	26 mi LOS	8 hours	AES-256
TrellisWare TW-400 TSM CUB	10 oz	2 W	8 Mbps	8	26 mi LOS	8 hours	AES-256
Persistent Systems MPU4	13 oz	2 W	41 Mbps UDP 31.1 Mbps TCP	Unlimited	26 mi LOS	14 hours	AES-CTR-256 with SHA-512 HMAC
Persistent Systems MPU5	13 oz	6 W	100+ Mbps	Unlimited	Up to 130 mi	12 hours	AES-CTR-256 with SHA-512 HMAC

Adapted from Harris Corporation (2019); Persistent Systems (2016a); Persistent Systems (2017); TrellisWare (2016); and TrellisWare (2019).

After we selected radio systems for our network data link, we researched the best solutions for our control link to integrate with RMP-400 unmanned vehicle. A control link is a link between an unmanned system and a controller that an operator will use to maneuver it. Since, in our network architecture, our goal was to keep operators at a safe distance from dangerous or unknown areas, a control link had to be long-range capable. We also wanted our control link to be low-bandwidth and to not require extensive resources to maintain it.

We examined HopeRF LoRa technology, specifically LoRa Module RFM95W (Figure 32). It is a long-range modem of low power consumption that supports low-bandwidth data exchange (HopeRF, 2018). LoRa devices are currently used for wireless alarm and security systems, long-range irrigation systems, automated meter reading, and other similar industrial products. This modem supports 64-byte payloads which means it could be used to transmit and receive short text messages or commands.

Figure 32. LoRa module. Source: HopeRF (2018).

Using an expansion board like the one in Figure 33, this LoRa module can integrate with Raspberry Pi computer and programmed to integrate with RMP-400 for peer-to-peer communication. The manufacturer gives users access to certain design parameters to enable them to customize LoRa for a given application as required (HopeRF, 2018). Unfortunately, we were unable to have access to LoRa modem in time to prepare for our bench-testing phase and made a decision to implement goTenna Mesh radios for our network control link.

Figure 33. Raspberry Pi+ LoRa expansion board. Source: Uputronics (n.d.).

We thoroughly studied the properties of goTenna Mesh and goTenna Pro during the literature review phase. We were unable to acquire any goTenna Pro systems and determined that goTenna Mesh properties fit our requirements for a control link system. This radio supports low-bandwidth test message exchange, PLI, and GPS data, and does not require any pre-existing infrastructure only a smartphone. It can work as a node as wells as a relay, which can potentially extend the range between an operator and an unmanned system. Additionally the manufacturer provides goTenna software development kit (SDK) to users to integrate the radio with other devices such personal computers or laptops and Raspberry Pi for customization.

b. Antenna Equipment

During the San Clemente experiment, the network backbone nodes were connected to Persistent Systems Sector Array antennas. The Sector Array is an omnidirectional antenna that consists of three individual sectors providing 120-degree area coverage each (Figure 34).

Figure 34. Sector array radio router. Source: Persistent Systems (2014).

What we observed during MTX was that this sector array antenna system was very limited in range. The nodes were positioned in such way that each node was in line of sight of at least two neighboring nodes to provide a clear path from the farthest node to the TOC. The distance between the antenna nodes was only a few miles and we did not experience any issues with the network link. However, the communication with a ship that participated in MTX and was located approximately 20 miles from the TOC was unsuccessful. We were able to establish communications between the ship and the TOC, but the link was very unstable due to the range to the ship and its continuous movement along the coastline. This observation prompted up to consider using a combination of both directional and omnidirectional antennas in our network architecture to benefit from the advantages of both.

We decided to equip our RMP-400 unmanned vehicle with a directional antenna built by Bourakov. This self-aligning directional antenna consists of a pan-tilt unit PTU-300 providing flexibility of movement for the antenna, MPU4 radio board, Raspberry Pi+ board, Inertia Measurement Unit (IMU) that tracks antenna's angular motion, and a network switch (Figure 35).

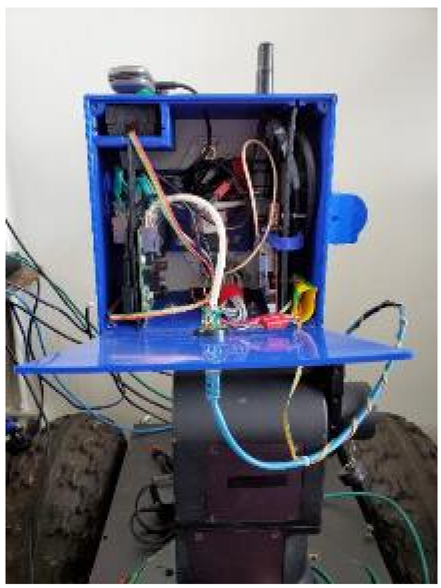


Figure 35. RMP-400 self-aligning directional antenna

The omnidirectional antenna we selected was a 600 mW, 5GHz, dipole antenna that was attached to a Wave Relay quad radio (Figure 36). The antenna alignment script was written by Bourakov in Python programming language and Node.js platform (Appendix A). We intended to use omnidirectional antennas at the TOC since we expected our network nodes to be in different directions relative to the central node.

Figure 36. Omnidirectional antenna with Wave Relay quad radio

C. PHASE II – BENCH TESTING

Our bench-testing phase consisted of testing antenna and radio nodes at NPS and extending the communication links from NPS to Presidio of Monterey and to Santa Cruz. We also observed basic navigation operations of RPM-400 at Camp Roberts.

1. Directional Antenna Testing

We began our bench-testing phase with the evaluation of the antennas selected for our experimentation. The self-aligning directional antenna was placed 160 feet above ground on the roof of Spanagel Hall at NPS. The omnidirectional antenna was attached to the roof of our vehicle using four suction cups. Each antenna was connected to a laptop to create a peer-to-peer network of two nodes. We then drove from NPS to Presidio of Monterey Franklin Gate 2.2 miles away (Figure 37).

Figure 37. Self-aligning antenna range test

During the drive, we used a ping tool to verify connectivity to the laptop that is connected to the directional antenna at NPS. A ping is a network tool used to test the reachability of one node to the other. We observed that the self-aligning antenna was successfully able to follow the omnidirectional antenna when our vehicle bearing to it was changing and there was an unobstructed line of sight between the antennas. In the areas where the view of the directional antenna was obstructed from us by trees or buildings, we could not ping the other node and directional antenna was losing tracking. However, once the two antennas were in clear sight of other another, the directional antenna was able to reacquire the link and communication path would reestablish. This experiment demonstrated that the self-aligning antenna can maintain the line of sight communication link when relative bearing between antennas changes and that it is able to reestablish the link that is lost due to obstructions when required.

2. RMP-400 Testing - Basic Navigation and Communications

During the February 2018 JIFX, we took the RMP-400 to Camp Roberts Combined Arms Collective Training Facility (CACTF) to observe its terrain performance, obstacle maneuvering, and ability to carry communications sensors inside buildings and tunnels, which could be encountered during special operations missions. To test these items, we performed a series of three experiment segments.

For basic navigation, the RMP-400 has a fairly simple controller in the Android device (Figure 38), but it takes some time to master dexterity of it. To comfortably operate it, an operator would need to practice their driving and speed control skills at least two to three times before operating in the field. Due to the rugged ATV wheels, the RMP performs very well in dusty and rocky terrain. It also did not have any issues moving up or down steep inclines, despite its heavy size, even when carrying additional communications payloads.

Figure 38. RMP-400 terrain test, Camp Roberts CACTF, February 2018

After our basic navigation testing, we participated in a radiological nuclear (RADNUC) material detection scenario, in which faux RADNUC material gives off a RADNUC signature, was hidden in the CACTF site building. We added a RADNUC detection sensor to the RMP, tied into the onboard MPU4 radio, and drove it inside an old CACTF building's main and basement floors. We were observing two parameters with this experiment, 1) how the RMP performed in tight spaces with obstacles, and 2) whether the RMP could pick up a RADNUC signature and alert the operator in a real-time manner. The RMP did very well with navigating obstacles, getting through doorways, and climbing down the stairs to the basement level. It also gave a timely alert when it approached the hidden faux RADNUC material, proving that RMP could

Figure 39. RMP-400 obstacle maneuvering test, Camp Roberts CACTF, February 2018

The third part of our experiment involved testing the maneuverability and sensor detection of the RMP in a tunnel, as seen in Figure 40. The tunnel was approximately 20 feet long, ran horizontally along the ground, and was made of concrete. We used the faux RADNUC material, hidden in an undisclosed location in the tunnel, and equipped the RMP with the RADNUC sensing equipment again. RMP was easily able to navigate downhill to the mouth of the tunnel and enter it, with the use of the Android control application. As it slowly moved into the middle of the tunnel, near a small drop out area in the concrete, the RADNUC sensor alarmed and alerted an operator about 150 feet away in another area of the CACTF. This was an excellent demonstration of using a UGV to extend the network and perform sensor detection, while maintaining reach back to operators.

Figure 40. RMP-400 tunnel sensor test, Camp Roberts CACTF, February 2018

3. GoTenna Range Testing

Following the testing of our directional antenna and the unmanned platforms, we began testing our goTenna by extending its range of operations as far as possible while maintaining the link. In this experiment, we used three goTenna Mesh devices. The first device was mounted on an antenna post on the roof of Spanagel Hall at NPS as node 1 (Figure 41), the second one was taken to Moss Landing area, approximately 15.3 miles from NPS, as node 2, and the third one was set up near the Santa Cruz Surfing Museum, approximately 16.7 miles from Moss landing and 25.8 miles from NPS, as node 3 (Figure 42). Node 2 was intended to be a relay node between node 1 and node 3.

Figure 41. Node 1 set up

Node 1 consisted of a goTenna and a smartphone. It was located approximately 160 feet off the ground clear of trees and other obstructions in its view. Nodes 2 and 3 consisted of a goTenna and a laptop (Figure 43) and were at the ground level at both Moss Landing and Santa Cruz locations. Node 1 was set to continuously send out a beacon, or heartbeat message, once a minute to be relayed by node 2 to node 3. Once we verified that node 1 beacon was successfully received by node 2, we confirmed the link between nodes 2 and 3 was up. Once all three nodes were online, we tested the transmission from node 1 to node 3 via node 2.

Figure 42. goTenna mesh range testing

Each message that nodes 2 and 3 received was displayed on dashboards connected to each respective laptop and had a time stamp and number of hops between the originating node and the destination. We discovered that although node 2 was receiving the messages from node 1, it was not relaying them to Node 3. However, though intermittently, node 3 was receiving messages directly from node 1.

Figure 43. goTenna laptop connection

Since node 1 was steadily transmitting to node 2 almost 16 miles away, we expected the link of similar range between nodes 2 and 3 to be up as well. As previously mentioned, node 1 was elevated off the ground and nodes 2 and 3 was on the ground level.

In a follow-on goTenna range test, we only tested the link between two nodes. Node 1 remained on the roof of Spanagel Hall at NPS and node 2 was taken by Eugene Bourakov on a small plane that flew from the Monterey Regional Airport to NPS and then to Santa Cruz at 3,000 feet altitude (Figure 44). Once the link was established between the two nodes, it remained steady and unbroken throughout the experiment.

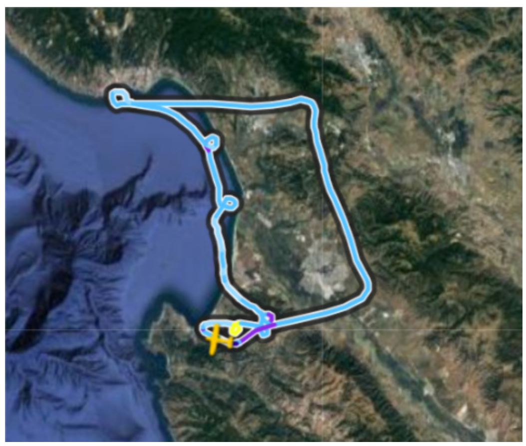


Figure 44. goTenna testing at 3,000 feet altitude

These two experiments showed that elevation played an important role in extending the transmission range well beyond the manufacturer's specification of a four-mile maximum range for peer-to-peer communications (goTenna, 2019b).

D. PHASE III – FIELD EXPERIMENTATION

In this phase, traveled to Camp Roberts to test the goTenna system's ability to transmit control data between TOC and RMP-400. We also conducted a joint experiment with our BGU colleagues that integrated IVO and MPU5 systems and tested the network data link.

1. Control Link Experiment – RMP-400 and goTenna

Our field experimentation included testing and evaluation of network control and data links. We began this phase with a control link experiment at Camp Roberts, California, during February 2019 JIFX 19-2 event. For this experiment, we used three goTenna Mesh radios, one to be located at the TOC as node 1, one to serve as a relay node 2, and one to be attached to the unmanned vehicle and RMP-400 as node 3. The self-aligning directional antenna was also attached to RMP-400 (Figure 45).

Figure 45. RMP-400 with direction-finding antenna attached

Bourakov programmed node 3 goTenna device to integrate with RMP-400 using Raspberry Pi+ computer (Figure 46) using application programming interface (API) written in Python 3.7 (Appendix B) and control payload script written on Node.js platform (Appendix C). Once programmed, the radio was then secured to RPM-400. Bourakov also created a user interface for the RMP-400 mission control we utilized for transmit movement commands to the vehicle.

Figure 46. goTenna and Raspberry Pi+ for RMP-400

Figure 46 shows the location of all three nodes. The distance between node 1 and node 3 was approximately 3.86 miles; however, due to a hilly terrain of Camp Roberts, there was no direct line of sight between the two nodes. To mitigate that, we placed node 2 approximately 4.13 miles north-west of node 1 and 2.99 miles south-west of node 3 (Figure 47).

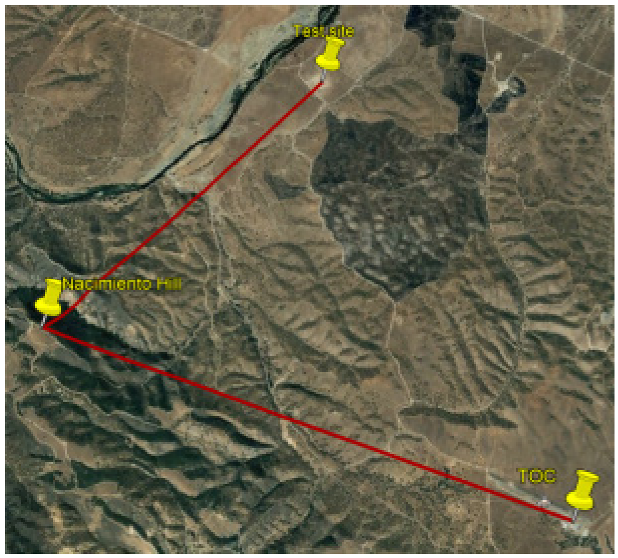


Figure 47. Control link path

Once all three nodes were online, we confirmed the communication flow by sending test messages between node 1 and node 3. We noticed a slight delay ranging from 3 to 9 seconds in message transmission. However, all messages sent by one node were received by the other via the relay node. We then attempted to calibrate the self-aligning antenna by sending command "CALIBRATE" from the goTenna user interface. If the command executed successful, the antenna would calibrate itself to point in the direction of the TOC. The antenna calibration was successful. The next step was to request PLI from RMP-400 by sending the command "STATUS" from the TOC. RMP-400 received PLI request, but did not send its GPS coordinates back to the TOC. We repeated this event four more times and were unsuccessful in each.

The last part of the test involved controlling the movement of RMP-400 by way points. On the mission control console, we identified four way points (WP) and created a WP1-to-WP4 route (Figure 48). Once the script was activated on the mission control interface, it was send to RMP-400 via goTenna user interface at the TOC.

Figure 48. WP1 to WP4 route

The first mission was unsuccessful, as RMP-400 did not move to WP1 to execute the command. After a few adjustments to the antenna, cycling the radios, and clearing the mission control interface, we created a WP3-to-WP4 route. RPM-400 sounded audio acknowledgement "mission activated" and proceeded to move to WP3 to begin executing the given route. The mission was complete once we heard "mission accomplished" and RMP-400 stopped at WP4.

During this experiment, we successfully demonstrated that a low-bandwidth, long-range radio such as goTenna can be integrated with an unmanned vehicle to provide the operator a control link for vehicle maneuvering.

2. Data Link – IVO and MPU5

During our April 2019 trip to Israel, we conducted a multi-stage experiment with BGU's LASR IVO remote driver system. The experiment was performed in a remote portion of the Negev desert for safety and emissions control reasons. Figure 49 shows IVOs operating area. Since our experiment involved IVO being controlled remotely from a distance, it is imperative that experimentation was performed in a non-public environment to avoid any unforeseen accidents. Additionally, since a large part of our test involved testing communications equipment, we did not want to be near anything that may cause transmission interference. The following equipment was utilized: One (1) IVO System, two (2) MPU5 radios, two (2) goTenna antennas, three (3) laptops, one (1) joystick video game controller, one (1) standard truck, two (2) tripods, one (1) collapsible table, and various ethernet cables, USB cables, electrical tape, zip ties, and Velcro straps.

Figure 49. Negev desert IVO operating area

The first step of the experiment involved configuring the communications equipment and installing the IVO system into the driver seat of the BGU truck. We set up a small foldable table with chair for the BGU laptop that would be receiving the IVO video feed and controlling it remotely via joystick controller. We named this our *base location*.

The table also held an NPS laptop with a goTenna connected via USB cable, which ran the goTenna program for communication to the remote goTenna. One MPU5 was affixed to a 5-foot tall tripod about 5 feet from the table and connected to the BGU laptop via ethernet cable (Figure 50).

Figure 50. Initial MPU5 5-foot tripod configuration

The second MPU5 was secured to a very strong magnet that was stuck on the roof of the BGU truck, with an ethernet cable running inside the truck window and connecting into the IVO unit (Figure 51). The second NPS laptop was inside the BGU truck, connected to the goTenna via USB. For better signal strength, the goTenna was taped to the outside, back passenger window with the USB cable running inside to the laptop, as shown in Figure 52.

Figure 51. MPU5 attached to roof of BGU truck

Figure 52. goTenna taped to BGU truck window

After a quick initial test run, we discovered that the 5-foot tripod was not tall enough to counteract minor LOS issues with hills and trees. The signal dropped out after only roughly 150 meters. Luckily, the BGU team had another taller tripod, roughly 8 feet tall, so we quickly affixed the MPU5 to that tripod instead.

Figure 53. MPU5 configuration with new tripod

After the short tripod was replaced, all our communications equipment tested satisfactorily so we commenced the first official experiment run. The BGU truck, with IVO, MPU5, goTenna, and Safety Observer, head out on a path 700 meters from the base location before we experienced a lag in video feed from the IVO. Once the lag occurred, the safety observer took over driving operations via the onboard controller. Without real-time video feed, the IVO cannot be operated remotely because the remote operator can no longer see the video feed. The BGU personnel had desktop recording set on the base location laptop so they could record all of the network parameter information for later processing. We also had the MPU5 Wave Relay management software signal to noise graph running on the laptop as well, to capture the radio's network performance. During this first official run, the goTenna communication worked well, with both short message chatting and beacon messages being sent and received between the two NPS laptops.

Figure 54. BGU truck with IVO and safety observer

Figure 55. BGU laptop screen with IVO display and joystick controller

For the second experiment run, the BGU truck with IVO driver, MPU5, goTenna, Safety Observer, and NPS student drove to roughly 800 meters from the base location before the video feed started to lag and then completely froze. The BGU truck then drove back in the other direction, in which communications were established again, before dropping out around 800 meters in the other direction. The BGU truck was able to reach a higher point of terrain, in which they could see the area of the base location, but we believe that the eucalyptus trees were causing LOS issues. The goTenna connectivity was lost at about the same range. Because we did not have a longer antenna tripod for the base location MPU5 nor did we have a secondary location to run the experiment without the tree LOS interference, we concluded the experiment and retrieved the network performance data for the IVO and MPU5 radios. This performance data will be discussed in our data analysis chapter.

Figure 56. IVO driving inside BGU truck

IV. OBSERVATION AND ANALYSIS

This chapter provides observations and analysis of our Phase II bench testing and Phase III field experimentations based on the data collected. We also analyze the capabilities of the systems we selected to support the network architecture relevant to our scenario.

A. OBJECTIVES

The goal of our research was to help lessen and possibly eliminate the risk to human operators in the field when constructing and maintaining communications networks for special operations teams. We focused our research on the capabilities of current antennas, radios, and unmanned ground systems, and how they could be incorporated into the construction of a self-moving tactical network.

1. Research Question I:

What unmanned platform characteristics are suited for constructing and delivering tactical network in an austere environment?

This question was investigated by examining all of the unmanned vehicles available to us against our main evaluation criteria: 1) equipment availability; 2) payload capacity; 3) range; 4) user control unit; and 5) speed. We originally researched a variety of unmanned vehicles but narrowed our focus specifically to ground vehicles for their smaller footprint, ability to move in a less detectable manner than UAVs, and their ability to provide better ground domain options than UMV. Additionally, UGVs generally do not require special licenses or operator courses for control like USV or UMV often require. RMP-400 and IVO both exceeded our criteria for use in tactical network operations and successfully completed the experiment parameters we built for them.

2. Research Question II:

What communications equipment characteristics support a short-term, self-moving tactical network in an austere environment?

This question was investigated by examining the radio and antenna systems for the network control and data links. We selected COTS goTenna Mesh system for the control link due to its experimentation availability, ease of use, and its ability to transmit and receive text messages across 25 miles LOS. The system was reprogrammed from its original settings and was redesigned to exchange control information such as RMP-400 calibration status, PLI, and movement commands. For the network data link, we determined that Persistent Systems MPU5 was suited to support data and video transmission in our network architecture. We chose to use the self-aligning directional antenna that was built and programmed by Bourakov and installed it on RMP-400. This direction-finding antenna was able to successfully acquire and maintain the link with the TOC.

B. EXPERIMENT RESULTS

During our bench test and field experimentation phases, we observed the network behavior that allowed us to determine whether the systems we selected were capable of supporting our network infrastructure. We provide the analysis of our findings in this section.

1. Directional Antenna Testing

Our first bench test consisted of an assessment of our self-aligning directional antenna. In this experiment, the directional antenna was following an omnidirectional antenna that was attached to a moving vehicle. The antenna first calibrated itself and locked in on the vehicle as we began moving. We discovered that during the 2.2-mile drive, the directional antenna lost the link several times due to the trees and buildings obstructing the view of the omnidirectional antenna. However, the antenna successfully reacquired the link once the view to the moving vehicle was unobstructed.

In order to have a steady communication link between the self-aligning antenna and an omnidirectional antenna we ensured that both are in a clear sight of each other with minimal or no obstructions. The directional antenna was able to recalibrate and lock in on the moving vehicle after every time the link was broken. In a tactical environment, it is essential to have a solid communication link at all times, as any delays in information exchange can have serious implications hindering the mission. The antenna's automated process of reacquiring the link reduced the communication delay to only a few seconds. Therefore, for our architecture, self-aligning directional antennas can support moving nodes by maintaining communication links between them.

2. RMP-400 Testing - Basic Navigation and Communications

For our first basic navigation test, the RMP-400 has a fairly simple controller in the Android device (Figure 38), but it takes some time to master the dexterity of it. To operate it comfortably, an operator would most likely need to practice their driving and speed control skills at least two to three times before operating it in the field. Due to the rugged ATV wheels, the RMP performs well in dusty and rocky terrain. It also did not have any issues moving up or down steep inclines, despite its heavy size, even when carrying additional communications payloads.

For the second bench test, RMP navigating obstacles deftly, getting through doorways, and climbing down the stairs to the CACTF building's basement level. It also presented a timely alert when it approached the hidden faux RADNUC material inside the CACTF building, proving that RMP could provide real-time updates on sensor alerts to remote operators in the field.

RMP performed as expected during the tunnel RADNUC testing as well, sending sensor data to remote operators in a timely manner. It also had no problem navigating the bumpy, tight terrain inside the tunnel and the partially underground space did not affect its communications or sensor equipment transmissions.

Overall, our RMP-400 bench tests were a realistic demonstration of using a UGV to extend the network and perform sensor detection, while maintaining reach back to remote operators. RMP met all of the criteria we were seeking in an unmanned vehicle.

Our tests confirmed that RMP could be used in tactical network environments for constructing and maintaining a mesh network.

3. GoTenna Range Testing

The purpose of the goTenna mesh radios bench test was to extend the range of the radio network to learn how far the network nodes could be located from one another while maintaining the communication. We also wanted to understand how elevation of each node affected network performance. Node 1 was approximately 160 feet above ground while nodes 2 and 3 were at the ground level. This positioning played a big role in how the communication flowed from node 1 to node 3. We learned that due to its higher elevation, node 1 attempted to establish the line-of-sight link with node 3 directly bypassing the node 2 relay, even though the connection was intermittent. We suspect that had the node 2 been placed at higher elevation than node 3, we would see the data going through it to node 3.

During the second part of this bench test, we only used nodes 1 and 2. Node 1 was in its original location on the roof of Spanagel Hall and node 2 was flown on a plane approximately 3,000 feet in the air. This time, we observed the link between the two nodes to be steady and unbroken at a 25-mile range.

We initially did not expect to see a successful communication link between the goTenna nodes beyond several miles. However, the nodes were able to communicate in unobstructed view of one another. This experiment showed that not only goTenna nodes must be in direct line of sight of each other, but that higher elevation yields a more stable communication link between nodes. GoTenna performance suggests that such system could support our tactical communications networks out to approximately 25 miles.

4. Control Link Experiment – RMP-400 and goTenna

We observed a similar performance of goTenna radios in the follow-on control link experiment in Camp Roberts. With significant elevation of node 2, we hoped to be able to establish a stable communication path between node 1 and node 3. The elevation of node 1 was 899 feet level, node 2 – 1,564 feet, and node 3 – 618 feet above sea level. Figure 57 shows elevations of all three nodes as calculated using Google Earth application. The peak elevation denotes the location of node 2 with clear and unobstructed line of sight to both node 1 and node 3.

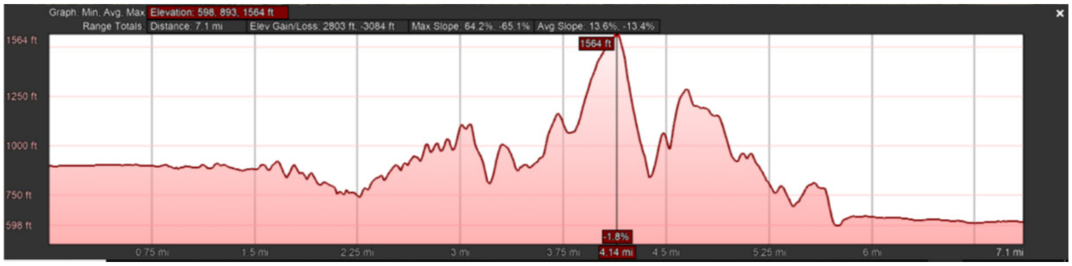


Figure 57. Google Earth elevation chart between network nodes

This facilitated a continuous data exchange between node 1 and node 3. We did notice a 3-9 second delay in transmission and a few messages were received in as long as 17 seconds. This was due to the time it took for the antenna script to be processed and executed. A delay in messages measured in seconds that we observed in this experiment is unacceptable when considering tactical scenarios where the data exchange has to be almost instantaneous. Our experiment consisted of sending and receiving location data, antenna calibration, and a basic movement command for only one unmanned vehicle. An increased number of unmanned systems in a network architecture can possibly task the control link in a way that goTenna nodes would not be capable of supporting. We do not know how the network would behave if another unmanned vehicle was added, but we predict that the transmission delay would increase.

Overall, goTenna system proved to be a good fit for a control link in our network architecture. This COTS system can be reprogrammed as a control link radio to transmit control commands to and from RMP-400 to include calibration, PLI, and movement requests based on GPS data. We concluded that goTenna radios perform well as relays and are able to extend the range between an operator and an unmanned system. Although we well-exceeded the advertised range for goTenna mesh radios, we did not extend the range of the antenna as far as we did during our bench test phase due to the time constraint. If more experimentations were available, we would have extended the range between the nodes beyond the initial experiment settings. Since we were able to successfully establish the communication link between goTenna nodes during the bench test phase at 25 miles, we would anticipate to see even better link performance at Camp Roberts due to higher node elevations.

5. Data Link – IVO and MPU5

For the field experiment, our goal was to test whether a COTS unmanned ground system could be integrated with our communications equipment to extend data link range. We did not retrieve data on IVO's internal computer algorithms for operation and video feed translation, as it was irrelevant to our study and we were not seeking to develop or alter an unmanned system control unit. The most important observational aspect for us was that IVO performed as programmed and connected intraoperatively with our communications equipment, providing optimal network performance.

The IVO system has many features that would make it desirable for military missions. It is lightweight and portable, fitting into a suitcase type container when not in use. It has a fairly simple operator control unit, utilizing a standard gaming joystick that most military members would be familiar with. Of note, the joystick did take a certain level of manual dexterity and those who were not previously familiar with video game style controllers may find it hard to use without practice. The joysticks on the controller are very sensitive and moving them in a forward/backwards and left/right direction is not an intuitive substitute for driving with a steering wheel and brake pedals. Another issue with IVO is that there is no mechanism for manually shifting the vehicle between park, drive, and various other shifting settings. Because all of our experiments required a safety observer in the car with IVO, the safety observer manually shifted between park and drive. BGU is actively working on a solution for this and it should not be an issue in future iterations of IVO.

Unfortunately, we did not obtain the communications range we were looking for with this experiment due to the geographic location. We did not anticipate that a desert environment with only small rolling hills and small groves of Eucalyptus would have such a negative effect on LOS communications. If we had more time to conduct another experiment before we left, a flatter location would have been ideal to test the extreme limits of the range in which the IVO could be controlled via MPU5. Additionally, affixing the base MPU5 to a higher location or small tower would have provided better results as well. Figure 58 and 59 are representations of the elevation along the paths that IVO took. The lowest point in Figure 58 was where our base location and tripod antenna was set up. At the time, the BGU team nor we realized that we were actually positioned in the lowest spot along the path. Being at the lowest elevation along the route contributed heavily to achieving ranges far shorter than we suspected to see. Our recommendation for future experiment design would be to terrain map the experiment areas elevation to find the highest ground base location set-up and to utilize a taller tripod system or affix to a permanent structure, such as a pre-existing communications tower.

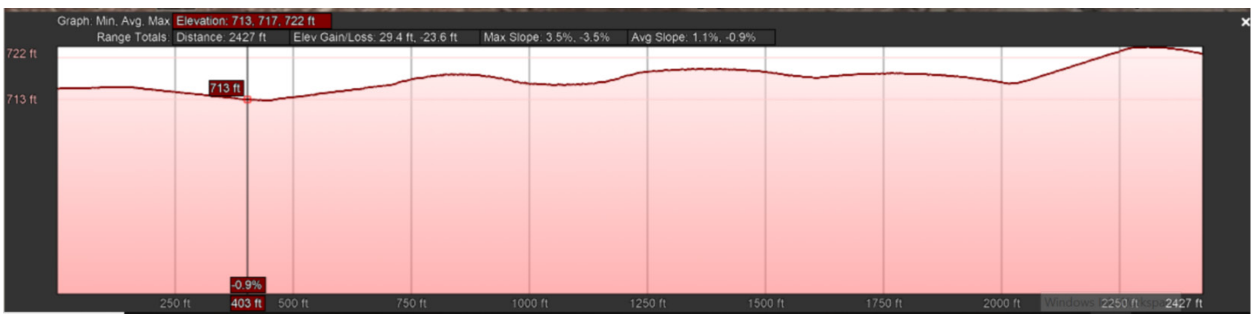


Figure 58. Negev desert elevation for IVO experiment- first run

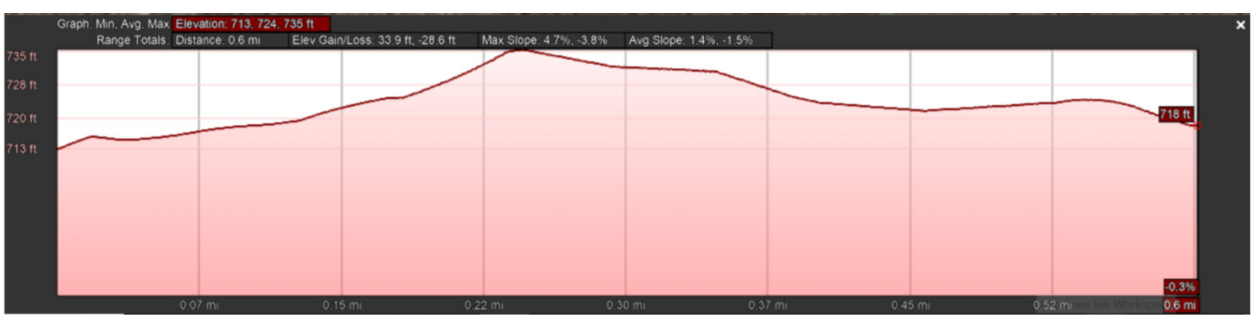


Figure 59. Negev desert elevation for IVO experiment- second run

Although the range was limited due to LOS issues, the MPU5 performance prior to reaching maximum range was in accordance with expected operating parameters, providing high throughput. This allowed us to see a clear, real time video feed from IVO so that we could control it via remote control. Figure 60 shows a desktop screen capture of the video feed from IVO to the remote BGU laptop. In addition to real-time video, the screen also displays the IVO battery status, kilometers per hour, azimuth, gears, and throttle. A major consideration for utilizing this system is the footprint size of the vehicle being used. If a small footprint is desired for clandestine operations, then vehicle size must be considered when selecting which vehicle IVO will be installed in. Overall, IVO's performance was well within our acceptable parameters for utilization in constructing and extending a tactical network.

Figure 60. Desktop screen capture on remote BGU laptop of IVO video feed

V. CONCLUSION AND RECOMMENDATIONS

This chapter provides a summary of our research, our motivation for concentrating on this problem area, conclusions for each of the areas examined, and recommendations for future research concerning self-moving tactical networks.

A. SUMMARY

The purpose of our research was to examine whether current unmanned vehicles and communications systems could be integrated to form short-term, self-moving tactical networks for special operations teams. We were not able to find any studies that directly addressed this topic so we researched equipment that could meet our criteria for this scenario and designed experiments to test its capabilities and limitations. Through this experimentation, we demonstrated the feasibility of constructing self-moving tactical networks with unmanned ground vehicles. Although we were constrained by equipment availability, geographic testing locations, and time, the experiments we conducted proved that UGVs could be utilized in network architecture construction to deploy and adjust nodes in the place of network operators.

B. MOTIVATION

Our research was motivated by the need to help lessen and possibly eliminate the risk to network operators in the field when constructing and maintaining communications networks for special operation team missions.

C. CONCLUSION

This thesis examined the technical specifications and capabilities of available radios, antennas, and unmanned ground vehicles through a series of experiments as they pertain to rapid integration and deployment of tactical networks for special operations teams.

1. Communications Equipment Conclusion

Based on our observations and analysis of the bench-testing and field experimentations, we concluded that commercial solutions such as goTenna systems and Persistent Systems MPU5 radios could provide a viable solution to extend the control and data link range between unmanned systems and network operators. We note that node elevation plays a vital role in the range extension between nodes and higher elevation yields longer range due to unobstructed view of the nodes. A combination of omnidirectional and self-aligning directional antennas can support a network of unmanned vehicles to facilitate remote control and data exchange between the vehicles and their operators.

2. Unmanned Vehicles Conclusion

Unmanned vehicle technology continues to evolve at a rapid pace. In the culmination of this research, UGV have proven well suited to the task of network construction and deployment. Allowing unmanned vehicles to assume the role of network operators greatly reduces the risk to life that is present in austere environments, such as hostile enemy fire or natural disaster. As unmanned technology progresses, it should be constantly evaluated to understand how it could be incorporated into military operations and provide maximum benefit to the U.S. military.

3. Research Question Conclusions

Our research questions were thoroughly examined within the scope and limitations of our thesis, and we demonstrated results that support unmanned vehicle utilization in the rapidly construction and deployment of networks for special operations missions. Although our experiments were successful, there is much that can be done to improve network range and performance in future experiments.

D. FUTURE RESEARCH

This section includes recommendations for continued research concerning each subject area we covered for our thesis work. Although we recommend several options for each area, based on our knowledge of current and emergent technology, it is not an exhaustive list.

1. Communications Equipment – Antennas and Radios

We recommend focusing efforts on new antenna and radio technologies and explore their capabilities and potential to provide greater range and throughput than we were able to achieve. Future experiments could include the use of miniature phased array radars mounted onto UGVs and the TOC for omnidirectional transmission. This would eliminate the need for pan-tilt or rotation mechanisms allowing for rapid scanning and network optimization. These antennas are usually lightweight and smaller than some traditional antennas.

During our experimentations, we learned that although goTenna radios are capable of transmitting control commands, the complexity of the script delays the transmission, which should be taken into consideration during mission planning. We recommend performing future control link testing with goTenna Pro systems to analyze the processing speed of goTenna Pro. Unlike goTenna Mesh, goTenna Pro radios can perform as relays automatically and do not require any configuration changes, it is possible that the transmission delays could be reduced. Additionally, since the transmission power of goTenna Pro is 5W, when compared to goTenna Mesh 1W power, we believe that the range of goTenna Pro nodes can be extended beyond a 25-mile distance we achieved during our experimentations (GoTenna, 2019a).

Figure 61. goTenna Mesh and goTenna Pro size comparison

We recommend further testing of Persistent Systems MPU5 Wave Relay radios. Due to environmental constraints, we were not able to achieve data link ranges advertised by the manufacturer. Conducting field experiments in areas with either higher elevation or unobstructed terrain can help better understand the capabilities of these radio systems in regards to self-moving tactical networks. We also suggest adding multiple nodes to the network architecture and testing communication data relay and exchange while monitoring the network performance.

2. Unmanned Vehicles

We believe that utilizing tethered rotorcraft for network construction could greatly expand LOS capability by allowing nodes to be visible in areas where higher ground elevation or tall structures do not exist. Elevating nodes via a tethered rotorcraft would provide a sustained power source for maximum station-keeping LOS during missions.

Exploring the use of small rotorcraft or UAV equipped with Light, Detection, and Ranging (LIDAR) technology would assist greatly in network construction by providing terrain mapping for provide real-time topographic information. This would help network operators in deciding the best location to move nodes for optimal LOS communications.

Researching fully autonomous cars could provide enhanced capabilities for network construction and adjustment through advanced machine learning built into the car itself. This high-level programming could expedite network construction and provide auto-adjustment for best LOS positioning. Additionally, studying the fairly new field of flying autonomous cars may also prove useful in understanding whether they could be integrated into tactical networking scenarios.

We encourage future interested parties to investigate emergent communications technologies, specifically lightweight, long-range devices. As communications equipment becomes lighter, our minimum payload criteria for unmanned vehicles could be reevaluated, resulting in the use of smaller unmanned vehicle with a less detectable footprint during tactical operations.

E. FINAL THOUGHTS

Our research stemmed from the identification of a major issue with current tactical networking procedures. There are no commercial solutions that currently exist to immediately resolve the problem of network operators being exposed to hazardous environments while configuring tactical networks. Our research does not provide a perfect solution for the problems associated with rapid deployment of special operations tactical networks, but it has laid the groundwork for further exploration into solving this issue. We hope that future students will advance our thesis topic by conducting follow-on experiments that integrate new and upcoming technologies.

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APPENDIX A. GOTENNA API

Appendix A is the goTenna API written in Python 3.7. This program was designed by Eugene Bourakov.

```
'use strict';
console.log('');

let moment = require('moment');
let express = require('express');
let app = express();
let cors = require('cors');

let path = require('path');
let _ = require('lodash');
let bodyParser = require('body-parser');
let errorhandler = require('errorhandler');
let notifier = require('node-notifier');

let contextBuilder = require('./appContext');
let context = contextBuilder.build({express: app});

console.log('---------------------');
console.log('Antenna Tracker '+context.version);
console.log('---------------------');

let pliDataManager = require('./services/pliDataManager');
let pliManager=new pliDataManager();

let socketListener = require('./services/socketListener');
let udpListener =  new socketListener();
```

```
udpListener.startListening(context);

let gotennaDataManager = require('./services/gotennaDataManager');
let gotennaManager=new gotennaDataManager();

//let imuDataManager = require('./services/imuDataManager');
//let imuDataMngr=new imuDataManager();
//imuDataMngr.startListening(context);

let ptuController = require('./services/ptuController');
let ptuCtrl=new ptuController();
ptuCtrl.start(context);

let ping = require('ping');
let pingConfigBasic = {
   timeout: 5,  // process for maximum of 5 seconds. Maps to '-t' ping option
   min_reply: 1, // send 1 ping. Maps to '-c' ping option
   extra: []
};

// catch Uncought Exception to prevent Node to crush (happense only on Raspberry
Pi with https request in wrservice.js)
process.on('uncaughtException', function (err) {
   console.error(err);
   console.log("Uncaught Exception, but Node is NOT Exiting...");
});

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~

// all environments
app.set('port', process.env.PORT || 8888);
```

```
// app.set('views', __dirname + '/views');
// app.set('view engine', 'jade');
// app.use(express.favicon());
// app.use(express.logger('dev'));
// app.use(express.methodOverride());
// app.use(app.router);
app.use(cors());
app.use(express.static(path.join(__dirname, '/')));
app.use(express.static(path.join(__dirname, 'public')));

app.use(bodyParser.urlencoded({extended: true}));
app.use(bodyParser.json());
app.use(bodyParser.raw());
app.use(bodyParser.text());

// development only
function errorNotification(err, str, req) {
   let title = 'Error in ' + req.method + ' ' + req.url;
   notifier.notify({
      title : title,
      message : str
   });
}
if ('development' == app.get('env')) {
   app.use(errorhandler({
      log : errorNotification
   }));
}

app.get('/', function(req, res) {
   console.log("GET /");
   //res.send('This is an antenna tracker web access root');
```

```
    res.redirect('dashboard.html');
});


let server = app.listen(app.get('port'), function() {
    let host = server.address().address;
    let port = server.address().port;
    console.log("Listening at http://%s:%s", host, port);
});

// initialize Java WRsnr process to collect neighbors' SNR and GPS
var exec = require('child_process').exec;
exec('java -jar WRsnr.jar', function callback(error, stdout, stderr){
    console.log(stdout);
});


//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~

function updatePTU() {
    ptuCtrl.updatePTU(context);
}
function getPliFromSa() {
    pliManager.getTrgPliFromServer(context);
}
function goTennaBeacon() {
    gotennaManager.sendGoTennaBeacon(context);
}
function pingNodes() {
    // check if peer nodes are accessible
    checkPing(context.localRadioIP);
```

```
    checkPing(context.trgRadioIP);
}

function checkPing(radioIP){
    ping.promise.probe(radioIP, pingConfigBasic)
        .then(res => {
            if(!res.alive){
                if(res.host==context.localRadioIP) {
                    context.pliLat=context.pliLon=context.pliAlt=null;
                } else {
                    if(context.trgLatSaServer=='') {
                        context.trgLat = context.trgLon = context.trgAlt = context.trgSNR
= null;
                    }
                }
            }
        })
        .catch(function (err) {
            console.log(err);
        })
}

setInterval(updatePTU, context.pollingInterval);
setInterval(pingNodes,3000);
setInterval(goTennaBeacon,60000);  // 1 minute beaconing
if(context.useSAPLI) {
        console.log('SA PLI data query is active');
        setInterval(getPliFromSa,2000);
}
//console.log('Mosquitto topic via LoRa: '+context.mqttTopic);
//setTimeout(imuDataMngr.captureGyroBias,3000);
```

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APPENDIX B. GOTENNA CONTROL PROGRAM

Appendix B is the goTenna control payload programmed on Node.js platform. This program was designed by Eugene Bourakov.

```
'use strict';
console.log('');



let moment = require('moment');
let express = require('express');
let app = express();
let cors = require('cors');

let path = require('path');
let _ = require('lodash');
let bodyParser = require('body-parser');
let errorhandler = require('errorhandler');
let notifier = require('node-notifier');


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let gotennaManager=new gotennaDataManager();

//let imuDataManager = require('./services/imuDataManager');
//let imuDataMngr=new imuDataManager();
//imuDataMngr.startListening(context);

let ptuController = require('./services/ptuController');
let ptuCtrl=new ptuController();
ptuCtrl.start(context);



let ping = require('ping');
let pingConfigBasic = {
   timeout: 5,  // process for maximum of 5 seconds. Maps to '-t' ping option
   min_reply: 1, // send 1 ping. Maps to '-c' ping option
   extra: []
};

// catch Uncought Exception to prevent Node to crush (happense only on Raspberry Pi with https request in wrservice.js)
process.on('uncaughtException', function (err) {
   console.error(err);
   console.log("Uncaught Exception, but Node is NOT Exiting...");
});

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

```
// all environments
app.set('port', process.env.PORT || 8888);
// app.set('views', __dirname + '/views');
// app.set('view engine', 'jade');
// app.use(express.favicon());
// app.use(express.logger('dev'));
// app.use(express.methodOverride());
// app.use(app.router);
app.use(cors());
app.use(express.static(path.join(__dirname, '/')));
app.use(express.static(path.join(__dirname, 'public')));

app.use(bodyParser.urlencoded({extended: true}));
app.use(bodyParser.json());
app.use(bodyParser.raw());
app.use(bodyParser.text());

// development only
function errorNotification(err, str, req) {
   let title = 'Error in ' + req.method + ' ' + req.url;
   notifier.notify({
      title : title,
      message : str
   });
}
if ('development' == app.get('env')) {
   app.use(errorhandler({
      log : errorNotification
   }));
}
```

```
app.get('/', function(req, res) {
  console.log("GET /");
  //res.send('This is an antenna tracker web access root');
  res.redirect('dashboard.html');
});


let server = app.listen(app.get('port'), function() {
  let host = server.address().address;
  let port = server.address().port;
  console.log("Listening at http://%s:%s", host, port);
});

// initialize Java WRsnr process to collect neighbors' SNR and GPS
var exec = require('child_process').exec;
exec('java -jar WRsnr.jar', function callback(error, stdout, stderr){
  console.log(stdout);
});


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function updatePTU() {
  ptuCtrl.updatePTU(context);
}
function getPliFromSa() {
  pliManager.getTrgPliFromServer(context);
}
function goTennaBeacon() {
  gotennaManager.sendGoTennaBeacon(context);
}
```

```
function pingNodes() {
   // check if peer nodes are accessible
   checkPing(context.localRadioIP);
   checkPing(context.trgRadioIP);
}

function checkPing(radioIP){
   ping.promise.probe(radioIP, pingConfigBasic)
      .then(res => {
         if(!res.alive){
            if(res.host==context.localRadioIP) {
               context.pliLat=context.pliLon=context.pliAlt=null;
            } else {
               if(context.trgLatSaServer=='') {
                  context.trgLat = context.trgLon = context.trgAlt = context.trgSNR
= null;
               }
            }
         }
      })
      .catch(function (err) {
         console.log(err);
      })
}
```

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